PLANT XYLEM ANATOMY, DENDROCHRONOLOGY AND STABLE CARBON ISOTOPES AS TOOLS IN RAINFALL RECONSTRUCTION IN SOUTHERN AFRICA

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ABSTRACT

Within South Africa there is a growing need for a high resolution proxy rainfall data set that goes back beyond the historic record. As a contribution to meeting this need four techniques for rainfall reconstruction are evaluated.

It is only from a new technique utilising measurements of vessel size and frequency in the cross-sectional xylem anatomy of archaeological charcoal that statements may be made on rainfall trends over the last 2000 years. These results indicate a general decrease in rainfall from 2300 BP to the present with a slightly wetter period during the Little Ice Age (1300 to 1800 A.D.). The results also suggest that present conditions are much drier than at any other time within the last 2000 years. The only limitations on this method are the resolution of the radiocarbon dates, a suitable distribution of sites and a calibration curve for the species analysed.

The microscopic identification of archaeological charcoal to genus or species level cannot be usefully applied to climate reconstruction because woody species grow under a wide range of environmental conditions. The most common wood type in the archaeological record from two sites in the Drakensberg mountains is *Protea roupelliae*. This species grows in variable rainfall from 760 mm at Suikerbosrand through to 1600 mm at Umtamvuna that encompasses any climate change which may have occurred over the last 2000 years. This method may, however, be useful in determining the anthropogenic impact on the environment. In this respect, the decline in *Protea* toward the present is attributed to an increase in the fire frequency in the area as agriculturists move in circa 400 years ago.

A significant correlation exists between $^{13}C/^{12}C$ ratios of *Eucalyptus* sp. and *Combretum apiculatum* wood cellulose and water consumption. There are, however no significant correlations between $^{13}C/^{12}C$ ratios and rainfall for either cellulose or charcoal of *P. roupelliae*. It is possible that these contradictory results may be attributable to the habitat of the two species. Unlike *Combretum, P. roupelliae* grows in a wide variety of habitats and on a wide range of soils types and depths as well as in very variable rainfall regimes. This would suggest that a range of ecophysiological factors and environmental variables probably account for these results. The highly significant correlations for rainfall and $^{13}C/^{12}C$ ratios for *C. apiculatum* are not

manifested in the sample charred at 400° C probably because the main components of wood are degraded at temperatures around 300°C. This indicates that $\delta^{13}C$ of charcoal cannot be used to develop long term rainfall chronologies.

In a re-evaluation of the dendrochronological potential of *Podocarpus* sp., 14 trees of known age were examined. Even though whole trunk cross sections were used in the analysis, a combination of poorly defined, locally absent and converging rings make age determination and cross-dating impossible. Future dendrochronological research in South Africa using *Podocarpus* is not justifiable, especially since whole trunk cross sections have to be used in the analysis, and *Podocarpus* spp. are rare and endangered. Using *Widdringtonia cedarbergensis* two more chronologies are added to the single chronology already available for this species. The development of these well-dated ring width index chronologies is hampered by a lack of an abrupt termination in late wood growth in many of the trees. Despite this limitation the results show that, with a large enough sample size, it is possible to develop well-dated ring width indices from *Widdringtonia*. Correlations between ring width indices and rainfall are not sufficiently high to reconstruct rainfall through time.

Maintaining a focus on dendrochronology, a 77 year stable carbon isotope chronology was developed using six trees from a site in the Cedarberg Mountains. The $\delta^{13}C$ record from the pooled trees at the Die Bos site does not correlate significantly with rainfall. This correlation is not significant even when the *Widdringtonia* stable carbon isotope record is de-trended for the anthropogenic CO_2 contribution. The *Widdringtonia* record does, however, indicate a strong correlation between stable carbon isotope ratios of tree rings and atmospheric $\delta^{13}C$ CO_2. This correlation is manifested by less negative $\delta^{13}C$ values from 1900 to 1947 and a clear decrease to 1977 which is very similar to that derived from ice core data, tree ring $\delta^{13}C$ chronologies from the Northern Hemisphere and recent Southern Hemisphere records. This is only the second chronology, and the first with annual resolution, to show a decline in $\delta^{13}C$ for the Southern Hemisphere.

The main contribution of this project to the development of a long rainfall record for South Africa is that it has focused future research on new species for dendrochronology and the development of a more substantial rainfall record from *P. roupelliae* archaeological charcoal.

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PREFACE AND ACKNOWLEDGEMENTS

This study arose out of the need, within South Africa, to develop a technique to determine changes in rainfall patterns through time. The very limited time range of our present regional data set means that the long term variability of water supplies in South Africa is poorly understood. South Africa urgently requires high resolution (annual basis) regional data sets going back for 300 to 400 years in order to develop hypotheses on future water availability.

I am indebted to a great many people who assisted me in this project. They are too many to mention individually but I am grateful to them all especially Dr William Stock, Dr William Bond and Dr Margaret Avery who provided the stimulation and support to continue. Their continued interest and advice are appreciated. I would also like to thank Dr Stock and Dr Avery for reading through this manuscript and earlier drafts.

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The research was carried out in the Palaeobotany laboratory of the Earth Sciences Division at the South African Museum. Without the use of Museum facilities the project would not have been possible. For this I would like to thank the Director, Dr M. Cluver, and the head of the Division Dr R.M. Smith. I would also like to thank all my friends in Earth Sciences for the pleasant environment in which I work.

The archaeological charcoal samples and radiocarbon dates from Mhlwazini Cave and Collingham Shelter were provided by Dr Aron Mazel of the Natal Museum. Throughout the project I have had the close co-operation of Dr Mazel. I would like to thank him for sharing his ideas with me and supplying me with both published and unpublished data.

The dendrochronology section of this project would not have been possible without the enthusiastic support of many members of the Laboratory of Tree Ring Research at the University of Arizona. For this I would like to thank the Director Dr Malcom Hughes. I would also like to thank Dr Steve Leavitt who initiated this co-operation and provided laboratory facilities for me at the Tree Ring Laboratory. Rex Adams supplied me with the *Widdringtonia* samples housed in Tucson and also taught me the basics of dendrochronology. Rex was always available when I needed him. Among others in the Tree Ring Laboratory I would like to thank are Mark Kaib, Shelley Danzer, Martin Munro, Richard Holmes, Gregg Garfin, Bob Lofgren and Henri Grissino-Meyer.

An extant wood collection came from nature reserves and wildlife parks administered by the National Parks Board, Natal Parks Board, Cape Nature Conservation and Transvaal Administration, as well as from many private farms. For this I am grateful to Dr Richard Newberry of the Transvaal Provincial Administration, Dr W.P.D. Gertenbach of the National Parks Board, Dr O. Bourquin of the Natal Parks Board, Guy Palmer, Nigel Wessels and SW van der Merwe of Cape Nature Conservation, the Alcocks of Mhlopeni Nature Reserve, David and Dorothy Green of the farm Rensburgspruit, Conrad Rocher of the farm Baviaanskrantz, Ed Hanisch and Dries Bester at the University of Venda, as well as many park wardens, game rangers and others.

The *Podocarpus* samples were specially cut for this project by Tinus Botha of Cape Nature Conservation and supplied to me by Dr Jeremy Midgley of the Department of Botany at the University of Cape Town.

Stable carbon isotope ratios as well as ring width measures were correlated with mean annual rainfall. These rainfall figures were obtained from the Weather Bureau (Dept of the Environment), the Computer Centre for Water Research, the National Parks Board, Transvaal Provincial Administration, Cape Nature Conservation and the Natal Parks Board. The co-operation of all of these bodies in this regard is gratefully acknowledged.

The *Eucalyptus* sample used in this project was originally grown not for this study but in an experiment designed to select for drought tolerant and productive *Eucalyptus* spp. by FORESTEK (D.R. de Wet Research station) in collaboration with the University of Cape Town. These samples were made available to the project through the co-operation of Debbie Le Roux, William Stock and William Bond of the Department of Botany at the University of Cape Town and Dirk Versfeld of FORESTEK.

Nicky Allsopp and Colin Potts helped me with the field work while Rina Krynauw helped to obtain many interlibrary loans. The backbone of this project has been Noël Fouten, Marilyn Pether and Lesley Edmonds, who have between them sanded, microtomed, sectioned, labelled and measured hundreds of pieces of wood to enable me to arrive at the conclusions presented in this thesis. These conclusions are my own, and I am also responsible for the opinions and research design of this thesis.

The stable carbon isotope analysis was carried out in the Archaeometry laboratory in the Archaeology Department of the University of Cape Town. I would like to thank all the people in the lab. for making my time spent there so pleasant. In this regard I would especially like to thank Stefan Woodbourne and John Lanham.

Without the support of Nicky Allsopp none of this would have been possible.

CHAPTER ONE

INTRODUCTION

Introduction

This thesis attempts to provide a better understanding of climate and environment change in the summer rainfall region of South Africa through the development of four different techniques in rainfall reconstruction. These techniques comprise vegetation and rainfall reconstruction using both taxonomic identification and xylem analysis of charcoal recovered from archaeological sites, dendroclimatology and stable carbon isotope analysis of tree rings and charcoal. The research concentrates on two archaeological sites in the Drakensberg mountains of Kwazulu-Natal and in the Cedarberg Mountains of the Western Cape Province of South Africa (Fig. 1).

Rationale for this project

In southern Africa, where large agricultural districts are in marginal rainfall areas, climate change could have significant socio-economic consequences. This has never been more evident than during the 1991/1992 drought in which millions of tons of maize were lost and many thousands of people were faced with starvation. Droughts such as these that throw into focus the need for better management of present water resources and the forward planning for the enhancement of the water supply. Such a focus requires a projection on the range of climates to be expected in the future. An examination of the past to predict future climates has recently gained universal acceptance with the establishment of the International Geosphere Biosphere Programme (IGBP) in the mid 1980s. In 1986 the South African Committee of the

Figure 1. Map of South Africa showing location of the two research areas

International Council of Scientific Unions approved the appointment of a special committee to develop South Africa's contribution to the IGBP. Subsequently the IGBP core programme Global Change and Terrestrial Ecosystems (GCTE) was established to improve our understanding of how terrestrial ecosystems would react to changes in atmospheric composition, climate and land use (Shackleton 1990 & Tyson 1991). The main aim of this GCTE programme is to develop the capability to predict the changes in climate, CO_2 and land use on terrestrial ecosystems. Many of these predictions are based on General Circulation Models (GCMs). However, without the support of long term accurate climate records, predictions developed from GCMs and elsewhere are questionable.

At present regional rainfall data sets do not extend over more than 100 years and register relatively short oscillations of climate (Tyson 1986). Since all climate research is based on this very limited data set, the ability to extrapolate from this research is questionable. It is therefore imperative that other methods for establishing longer records are developed. There are a number of researchers in South Africa presently working on climate and environment reconstructions. The foci of this research are in palynology, charcoal identification, micromammal studies, oxygen isotope speleothem measurements, oxygen isotope and aragonite-calcite ratios determined from mollusc shells and palaeoflood analysis (see Tyson 1986 & 1991; Deacon & Lancaster 1988; Tyson & Lindsay 1992). None of these studies have provided a high resolution (annual or decadal scale in millimetres) rainfall record extending back beyond the historical record administered by the Weather Bureau (Department of the Environment, Pretoria). Results are often contradictory with resolution over thousands rather than single, tens or even hundreds of years (Tyson 1986 & 1991; Deacon & Lancaster 1988; Tyson & Lindsay 1992).

Tyson (1986 & 1991) relies heavily for his interpretations on the few dendrochonological attempts available for South Africa. This record, however, is not sufficient to provide input into GCMs. The longest available tree ring sequence for the summer rainfall region of South Africa is that described by Hall (1976) for a single *Podocarpus falcatus* specimen from Karkloof in Kwazulu-Natal dated to the 13th Century A.D. The most basic proposition in tree ring research is that a tree forms a new ring every year. This is, however, not a biological certainty and is one of the first suppositions that has to be clarified when assessing the feasibility of a tree species for dendroecology or dendroclimatology (Lilly 1977). Lilly (1977) concluded that a combination of very indistinct growth rings, discontinuous rings, indistinct boundaries and deceptive macroscopic ring patterns makes tree ring analysis in South Africa very difficult. According to Lilly (1977) complete sections of trunk have to be used in order to determine tree ring series from South African trees. Despite this, attempts to obtain a corroborative series for the Karkloof *Podocarpus* specimen failed because of a lack of definition in the rings of the trees felled for the study (Tyson 1986). These attempts by Tyson to obtain long rainfall records throw into focus the poor quality of such records in South Africa.

In order to complement or replace present methods utilised in climate reconstruction in southern Africa, the development of new methods or the application of uncomplicated techniques for determining change in rainfall through time is vitally important. In summary, this thesis serves to evaluate four techniques for environment reconstruction. The primary objective is the development of one high resolution method for reconstructing rainfall over decades or even single years. A secondary objective is the development of a number of other techniques which may not have the same resolution but can be used to evaluate the results. The approach outlined develops each technique from a modern analogue through to the prehistoric material. In so doing it provides the first real attempt at focusing a range of techniques on the problem of reconstructing the rainfall for the summer rainfall region of South Africa. The purposes of applying each technique are outlined below.

Charcoal identification and relative abundance

A number of South African researchers have used the charcoal recovered from archaeological sites in the reconstruction of woody environments. The pioneering work in this field is that of Deacon (1979). Subsequently other workers have made contributions to the South Africa research field such as Prior (1983), Prior & Price Williams (1985), Dowson (1988), Tusenius (1989), February (1992b) and Wadley *et al.* (1992). The emphasis of these studies lay in a detailed analysis of climate and environment change through wood identification from xylem anatomy.

The identification of wood to genus/species level is possible because the different genera/species have distinctive combinations of anatomical features visible under the microscope (Panshin & De Zeeuw 1980; Barefoot & Hankins 1982; February 1996).

Wood when charred maintains its anatomical structure so that charcoal can also be identified by the characteristic arrangement of the different cell types (Salisbury & Jane 1940; Godwin & Tansley 1941; Hadac & Hasek 1949; Slavikova-Vesela 1950; Vernet 1973; Krauss-Marguet 1980; Vernet & Figueiral 1993).

Charcoal from archaeological sites represents the remains of firewood collected by people, who made specific choices on the types of wood they would use (Gandar 1982; Milton & Bond 1986). The archaeological record will, therefore, always be skewed in the direction of the favoured fuel wood, although environmental conditions will influence the species of wood available for collection. It is on this basis that environmental change can be inferred from changes in the charcoal record of archaeological sites (Chapter Three).

Xylem analysis

Wood anatomists have increasingly emphasised the extent to which vessel size and number can vary with climate (Carlquist 1977a & b; Baas & Schweingruber 1987; Wilkins & Papassotiriou 1989). All of these studies show that vessel size decreases while vessel frequency increases with increasing drought. Scholtz (1986) was the first to realise the potential significance of certain wood anatomical variables for explaining climate change. He proposed a new method by which charcoal from archaeological fires can be used to reconstruct climate. Scholtz's (1986) Ecologically Diagnostic Xylem Analysis (EDXA) is based on the relationship between plant anatomy, physiology and ecology. It is not designed to describe the anatomy of wood, but rather to measure a wide range of potentially ecoclimatically significant wood variables observable in a transverse section. The basic premise of Scholtz's hypothesis is that it may be possible to determine past climate by comparing measurements on the wood anatomy of charcoal from archaeological sites with similar measurements on a modern sample of the same species from areas of known temperature and rainfall (Scholtz 1986; February 1990 & 1992a).

Scholtz (1986), used wood charcoal from Boomplaas Cave, near Oudtshoorn in the Western Cape Province, to establish differences in wood anatomy which he attributed to climatic change. Because Scholtz's (1986) work was of a pioneering nature, and his research at Boomplaas Cave was a preliminary test for this methodology, few of the electron micrographs he used were suited to this project. In my Masters thesis

(February 1990) I expand on the work by Scholtz (1986) however, both Scholtz (1986) and February (1990) recorded climatic change over thousands rather than hundreds of years, and did not establish a modern database. Chapter Four of this thesis is a systematic application of Scholtz's (1986) methods designed to test the precision and applicability of his hypothesis.

Dendroclimatology

Within South Africa Dunwiddie and La Marche (1980) demonstrated the potential for using *Widdringtonia cedarbergensis* and Curtis *et al.* (1978) provided some evidence for the dendrochronological potential of *Podocarpus falcatus*. These initially promising results were, however, never fully exploited. The research outlined in Chapters Five and Six of this thesis builds on and expands these earlier works in an attempt to corroborate the results of the xylem analysis section (Chapter Four).

In dendrochronology the age of a tree is determined precisely through an assignment of each consecutive annual ring to the year in which it is formed. Variation in the width of these rings form the basis for cross-matching or cross-dating among specimens from the same locality. Ring width measures of a number of trees from the same locality which cross-match precisely are combined to form a chronology which is related to available meteorological records to form the basis for climate reconstruction (Fritts 1976).

In Chapter Five, the use of *Podocarpus falcatus* and *Podocarpus latifolius* in dendroclimatology is re-evaluated. The main aim is to assess the potential for using these two *Podocarpus* species in dendrochronological cross-dating and chronology development.

Dunwiddie and La Marche (1980) developed their tree ring chronology for a site in the Cedarberg mountains called Die Bos. This thesis I develops two new chronologies for cores and discs collected from a stand of known age trees at Algeria and Krakadouw (Chapter Six), also in the Cedarberg mountains. Comparison of the results for the two studies is important in determining the contribution to climate research of ring width measurements using *Widdringtonia cedarbergensis*.

Stable carbon isotope analysis

Once the charcoal from the archaeological sites has been identified (Chapter Three and Four) and the tree ring chronologies have been developed (Chapters Five and Six), the thesis explores the potential for using stable carbon isotope measurements in tree rings and charcoal as a potential record of rainfall change through time (Chapters Seven, Eight and Nine). Recent studies suggest that plant $^{13}C/^{12}C$ ratios not only react to $\delta^{13}C$ of atmospheric CO_2 levels but are also good indicators of water available to plants (Francey & Farquhar 1982; Freyer & Belacy 1983; Leavitt & Long 1989; Lipp *et al.* 1991 & 1994). These studies are based on the hypothesis that when CO_2 is absorbed by plants the heavier ^{13}C isotope is discriminated against relative to the lighter ^{12}C isotope due to diffusion during stomatal conductance and the kinetic effect of the chemical reaction as the CO_2 is absorbed by the enzyme RuBP carboxylase. With increased water stress, stomatal closure results in reduced CO_2 uptake and therefore less discrimination resulting in more positive stable carbon isotope values (Francey & Farquhar 1982). Ehleringer and Cooper (1988) sampled various species along a moisture gradient in California and identified a change in stable carbon isotope ratios from -24‰ in the driest habitats to -26‰ in the wetter habitats. In Chapters Seven and Eight the relationship between stable carbon isotope ratios of wood cellulose and the amount of water available to the plant is investigated in two *Eucalyptus* species as well as in the rings of the same *Widdringtonia* specimens that were used by Dunwiddie and La Marche (1980) in an attempt to establish the first climatically responsive tree ring record for South Africa. This relationship is also investigated in the charcoal and wood cellulose of both *Protea roupelliae* and *Combretum apiculatum* along a rainfall gradient (Chapter Nine).

CHAPTER TWO

CLIMATE

Introduction

As outlined in the previous Chapter, the primary objective of this thesis is the development of a technique for obtaining high-resolution proxy rainfall data for the summer rainfall region of South Africa over the last 2000 years. The rationale for doing this is inherent in the marginal nature of many of the agricultural districts of South Africa and the need to manage and plan for the water needs of the country. Compared to available instrumental and historical climate records of the Northern Hemisphere, the Southern Hemisphere has very few, and South Africa no, high resolution climatic time series that extend back for more than 100 years. Several researchers utilising various methods have been attempting to correct this imbalance (Deacon & Lancaster 1988). The emphasis of this research has, however, not been specifically directed at the last 2000 years. Generally information directed to this period is sparse, insufficient and often contradictory (Deacon & Lancaster 1988; Tyson 1986; Tyson & Lindsay 1992). Today, the arid nature of the South African subcontinent is strongly influenced by seasonal precipitation regimes which are often unreliable. This unreliability is of major socio-economic importance through its impact on agriculture. Focusing on rainfall, this section of the thesis outlines the main features of South African climates and palaeoclimates as a background to subsequent discussions.

Present day climates

Circulation patterns

A general feature of global atmospheric circulation is the tropospheric circumpolar westerly winds (Tyson 1986). Perturbations of these winds control daily weather. Within the Southern Hemisphere these perturbations are derived from three semi-permanent high pressure cells: The South Atlantic anticyclone, the South Indian anticyclone, and the East Pacific anticyclone. The main determinants of the climate of South Africa are the latitudinal position of the subcontinent which tapers from 20° to 35° S, the South Atlantic anticyclone, the South Indian anticyclone, and a region of pronounced convection activity, where three major near surface air streams converge, known as the inter-tropical convergence zone.

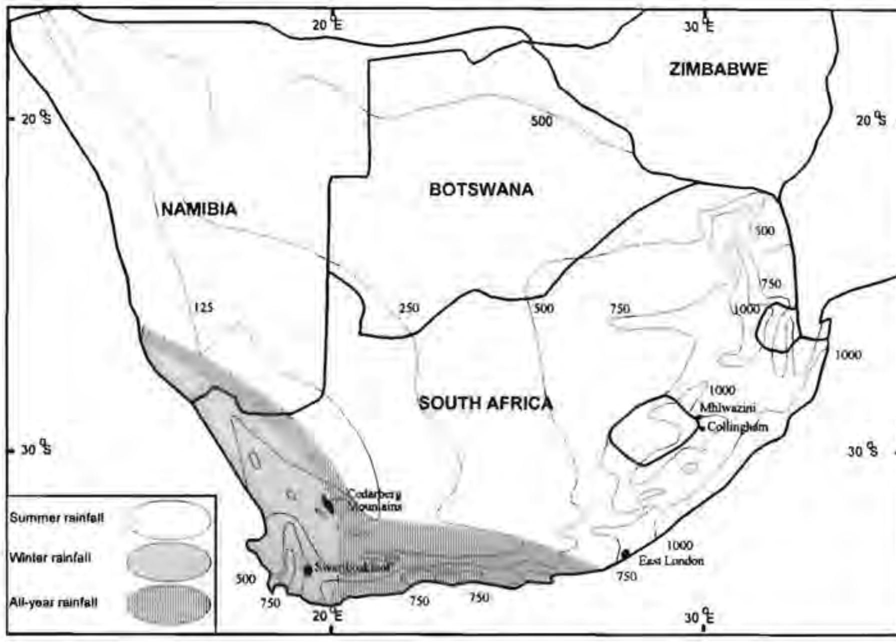

Figure 2. Seasonality and mean annual rainfall for the southern African Subcontinent (after Schulze 1972).

The main feature of the pattern of mean annual rainfall for southern Africa is the general decrease moving westward from a maximum along the east coast and Drakensberg escarpment to a minimum along the west coast (Fig. 2). Over almost the entire region rainfall maxima occur in summer. It is only in the Western Cape that there is a winter maximum of rainfall (Deacon & Lancaster 1988).

Wetter spells on the scale of days, seasons and years within the summer rainfall region are strongly influenced by a strengthening of the tropical easterlies as a result of the position of the inter-tropical convergence zone, which in summer lies just north of 20° S latitude, and a tropical low pressure cell located at 20° S latitude (Tyson 1986). This decrease in pressure over southern Africa is offset by an inverse in pressure over the South Atlantic since the South Atlantic Anticyclone situated in the vicinity of Gough Island at this time of the year is strengthened. A result of this interaction between tropical easterly and temperate westerly circulations is the formation of north-west to south-east convergence zones and cloud bands. These cloud bands are the major source of summer rainfall and convective activity. At the same time, the westerlies and their associated storm tracks are displaced southwards resulting in a reduction of rainfall in the southwestern part of the country. During winter the tropical easterlies weaken with a displacement of the inter-tropical convergence zone northwards and a weakening of the South Atlantic Anticyclone. A concomitant shift in the location of formation of interconnected tropical-temperate troughs and cloud bands occurs which results in a reduction in summer rainfall. In the south western part of the country, rainfall increases as the westerlies and their associated storm tracks are displaced northwards (Harrison 1986; Tyson 1986).

Figure 3. Position of the Drakensberg escarpment, the Soutpansberg and some of the locations mentioned in the text.

Rainfall

Atmospheric circulation patterns are responsible for producing rain; the amount of rain is, however, strongly controlled by relief or distance from the warm Indian Ocean (Lilly 1977). The low-lying coastal regions of Natal and the Transkei have high but extremely varied mean annual rainfall ranging from 1000 mm (Newcastle) to 1600 mm (Umtamvuna). Mean values are however closer to 1000 mm with higher rainfall areas occurring in pockets such as at Gillits (1400 mm) and Tugela River Mouth (1200 mm). South of East London (Fig. 2) the mean drops to 750 mm. The interior lowlands have a much lower mean annual rainfall than the coastal lowlands since the influence of the Indian Ocean on the rainfall is lost. This area called Arid Savannah receives on average between 300 mm (Messina) and 600 mm (Phalaborwa). The interior lowland is that area east of the Drakensberg escarpment, north of the Soutpansberg and east of Messina known as the Lowveld (Fig. 3). West of the

Lowveld, the Drakensberg escarpment rises steeply for 800 - 1500 metres (Fig. 3). This high mountain region extends southwards inland of the coast into the Cape Fold Belt mountains. The orographic effects of the Cape Fold Belt and the Drakensberg escarpment are very marked resulting in some of the highest rainfall figures for the country. The high mountain regions of the Wolkberg Nature Reserve (Fig. 3) in the Northern Province and Swartboskloof (Fig. 1, 34°00' : 18° 57') in the Cape receive a mean annual rainfall of 1600 mm but annual rainfall can exceed 2000 mm. Continuing west of the Lowveld, the Drakensberg escarpment falls off gradually to form the flat interior of the Transvaal known as the Highveld. Typical mean annual precipitation for this region is between 600 mm (Potgietersrus, Fig. 3) and 650 mm (Nylsvly, Fig. 3). Inland of the Cape Fold Belt and west of the Highveld lies the driest part of the country, the Karoo. Average annual rainfall for this region decreases from approximately 500 mm in the east to less than 100 mm over the north-western areas. Precipitation decreases progressively as one moves inland from the escarpment and east coast. The decline in amount of rain towards the interior and central western sector of South Africa is associated with an increase in the unreliability of this rainfall.

Palaeoclimatic Models

Climate research within South Africa relating to the last 2000 years has recently been reviewed by Tyson and Lindsay (1992). The following summary makes extensive use of their review.

Temperature reconstructions for South Africa over the last 2000 years are better understood than that of rainfall. The most highly resolved series is an oxygen isotope analysis of a speleothem from the Cango Caves near Oudtshoorn (33° 32' : 22° 14', Talma & Vogel 1992). From this data set it is evident that fairly regular changes have occurred in the Oudtshoorn region over the last two millennia. Other relatively detailed temperature records have been constructed using planktonic foraminifera (Herbert 1987) and oxygen isotope and aragonite/calcite ratios of *Patella* shells (Cohen *et al.* 1992; Cohen & Branch 1992). None of these techniques shows any trends in temperature change through time. Rather, the indication is that there have been fluctuations around a mean.

It would appear from the work of Butzer *et al.* (1978), Klein (1980), Cooke and Verstappen (1984) and others, that between 3000 B.P. and 2000 B.P. conditions in the summer rainfall region of South Africa were generally much wetter than at present (Tyson 1986). In addition, Smith (1992) has tentatively suggested a wetter period from a single flood event of the Orange river dated to about 2400 B.P.

The period from about 650 B.P. (A.D. 1300) to 100 B.P. (A.D. 1850) has been called the Little Ice Age, a world wide phenomenon that has not been as extensively documented in the Southern Hemisphere as it has been in the Northern. Existing evidence does, however, suggest that the Little Ice Age in South Africa was the coolest and driest period within the last 10 000 years (Tyson & Lindsay 1992). A reinterpretation of the tree ring data of Hall (1976) and Dunwiddie and La Marche (1980) by Tyson (1986) shows below normal tree growth from at least the fourteenth century to the mid sixteenth century in response to the cooler and drier conditions prevalent at the time. Climatic amelioration beginning about A.D. 1850 (100 B.P.) was manifested by warming and increased summer rainfall. The Karkloof tree ring sequence (Hall 1976) shows an increase in growth at about A.D. 1760 that may be associated with this amelioration (Tyson 1986).

Rainfall trends through the nineteenth century data are rather more ambiguous and there are two schools of thought. Acocks (1955) may have been the first to record the expansion of the Karoo veld into grassland. Early research intimated that any expansion of the Karoo into grassland was the result of bad farm management coupled with a general decrease in mean annual rainfall. More recently Tyson (1986), Vogel (1989) and Avery (1991) have shown that the case for progressive desiccation is unjustifiable. Rather, they propose that the situation has been very much more dynamic with fluctuations in rainfall around a mean with wetter and drier cycles.

Tyson (1986) and Cockcroft *et al.* (1987) produced a model to explain the observed rainfall/temperature changes through the last 2000 years. This model cannot, however, be positively tested without a much more refined data series that would include high resolution rainfall data similar to the temperature data from the Cango Caves speleothem. The Cango Caves speleothem is the only high resolution data series for South Africa. There is a pressing need for many more series from many more localities utilising a variety of techniques. The remainder of this thesis attempts to address this need.

CHAPTER THREE

CHARCOAL IDENTIFICATION AND RELATIVE ABUNDANCE AS AN INDICATOR OF VEGETATION CHANGE IN THE DRAKENSBERG

Introduction

In this thesis four different techniques in rainfall reconstruction are evaluated. The first of these techniques is the interpretation of environmental, and by implication climatic, conditions from wood identified from its xylem anatomy. Major components of most archaeological sites are stone, bone and charcoal with charcoal often being the most abundant plant material. Within South Africa a number of researchers have utilised the charcoal recovered from archaeological sites to provide information on climate and environment change (Deacon 1979; Deacon *et al.* 1983; Prior & Price Williams 1985; Tusenius 1989). In these studies, positive identification of the archaeological charcoal is achieved by comparison with photomicrographs of identified modern species. Changes in the relative abundance of identified woody species in successive stratigraphic layers within the archaeological site indicate changes in the vegetation mosaic and can thus provide biological evidence for climate change (Prior & Price Williams 1985; Deacon & Lancaster 1988). This simple method for determining environmental change should give further information for palaeoclimatic and palaeoecological interpretation that is independent of and could clarify data obtained by other independent measures such as micromammal analysis (Deacon *et al.* 1984; Avery 1995) and palynology (Scott 1984). Although charcoal found in archaeological contexts reflects human selection since people made specific choices on the types of fuel wood they would use, past assemblages containing the relevant indicator species can provide much detailed climatic information (Prior & Price Williams 1985; Tusenius 1989; February 1992b).

Methods

The research area from which archaeological samples were obtained is focused around Mhlwazini Cave (29°02'52"S:29°23'23"E) and Collingham Shelter(29°27'35"S:29° 47'45"E, Fig. 1, Mazel 1990 & 1992). Both sites are located at an altitude of 1800 m in the Natal Drakensberg region of South Africa. These archaeological sites are caves situated in the main geological formation of the area, the Clarens Formation of the Karoo Sequence. Ecologically the Drakensberg area is Highland Sourveld which is a pure grassland on the more level parts but may form a *Protea* savannah on the slopes (Acocks 1953). Erosion of the Clarens Formation forms the nutrient poor soils on which the main vegetation type, the *Protea* savannah belt, is located. Mhlwazini Cave is on a small stream which flows into a tributary of the Mhlwazini River below Gatberg whereas Collingham Shelter is situated on a tributary of the Kwa Manzamnyama River which in turn flows into a tributary of the Inzinga. Little evidence exists for any woody vegetation in the vicinity of Collingham Shelter, whereas the mouth of Mhlwazini Cave is well screened by afromontane vegetation.

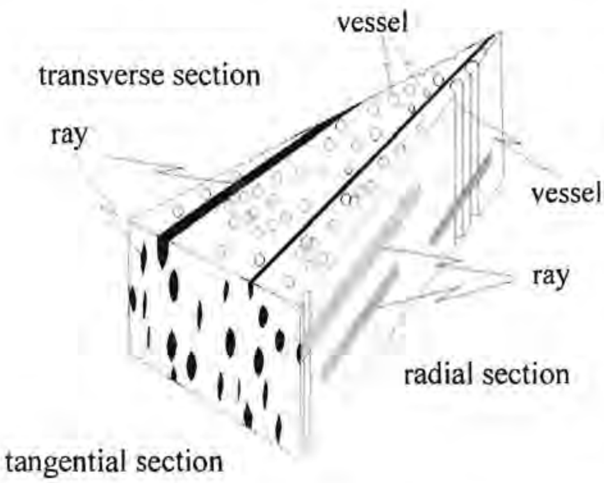

Figure 4. Diagram showing sections and main features of wood.

During the process of transpiration trees conduct water and dissolved minerals from the roots to the leaves via vessels (Fig. 4) and tracheids. Minerals and water can be stored in a separate group of less specialised cells (parenchyma) which are also depositories for waste material such as dissolved silicates. Trees and shrubs require mechanical support which is attained via yet another group of cells, the fibre cells. The characteristic arrangement of these various groups of cells in both horizontal and vertical planes makes it possible to identify wood to genus or species level. Wood when charred retains this anatomical arrangement so that wood charcoal can also be identified by the characteristic arrangement of the different cell types. Archaeological charcoal samples are identified by comparison with a charred reference collection which is usually obtained by sampling and charring the woody species growing in the vicinity of the archaeological sites today. Although not comprehensive, the species collection used to construct the reference consisted of (in alphabetical order) *Bowkeria verticallata, Buddleja salviifolia, Combretum spinosum, Carissa bispinosa, Cliffortia nitidula, Diospyros whyteana, Erica sp., Euclea natalensis, Greyia sutherlandii, Halleria lucida, Ilex mitis, Leucosidea sericea, Maytenus heterophylla, Myrsine africana, Podocarpus latifolius, Protea caffra, Protea roupelliae, Rapanea melanophoes* and *Rhus tomentosa.*

Although wood retains its distinctive anatomical features when charred, positive identification is hampered by wood anatomical variability. This variation is due to a number of ecological as well as physiological causes which have led researchers to emphasise the need for exhaustive tests on a single piece of wood to classify it taxonomically (Rendle & Clarke 1934; Carlquist 1980; Barefoot & Hankins 1982, Zimmerman 1983). In the present study it was decided to forego painstaking taxonomic identification in favour of developing a large body of data. As a result, 180 pieces of charcoal were analysed from Collingham Shelter and 390 pieces from Mhlwazini Cave. These samples were only examined in the transverse section (Fig. 4). For a more detailed taxonomic identification both radial and tangential sections would have to be analysed so as to confirm transverse sectional identifications (Fig. 4).

In the laboratory wood discs approximately three centimetres in length were cut and wrapped in aluminium foil. These parcels were placed in a muffle furnace at 400°C. After 30 minutes the furnace was switched off and allowed to cool overnight. The resulting collection, along with the publication by Kromhout (1975) was used in the identification of the archaeological charcoal samples. Six assemblages of charcoal from Mhlwazini Cave and three from Collingham Shelter were chosen for analysis. Both archaeological and extant samples were prepared for examination by physical fracture of each piece. A knife with a very fine serrated edge was used to make an incision perpendicular to the grain and through 360 degrees around the circumference of the piece of charcoal. The section was then snapped by placing the incision on a thumbnail and applying pressure with the left and right index fingers. The smoothest half of each section was mounted in "Prestik" on a glass slide. Once mounted the charcoal was ready for examination under a microscope. An inherent problem of fracturing charcoal for microscopy is that the prepared surface is rarely, if ever, absolutely flat. As incident light microscopes do not have the necessary depth of field to deal with an uneven surface a Nikon (Tokyo, Japan) Optiphot M dark field reflected light metallurgical microscope was used for identification purposes.

Results

Results show that the most common wood types in the archaeological record could be grouped into generic types (Table 1 and Fig. 5). Even though it is possible to separate *Diospyros* and *Euclea* on the basis of wood anatomical detail, this was not felt to be necessary for the present study since the added resolution would not affect the interpretation in any way. In all, nine genera were identified in the various assemblages of charcoal from well-dated archaeological units (Table 1). A further two categories were used for all wood not identified because of insufficient reference material or because of poor preservation (Table 1). Of the 540 pieces of archaeological charcoal examined, 49 pieces or 9 % were not identified because of insufficient reference material. Of the rest, the preservation was such that only 17 pieces were unidentifiable owing to a lack of structural detail (Table 1 and Fig. 5).

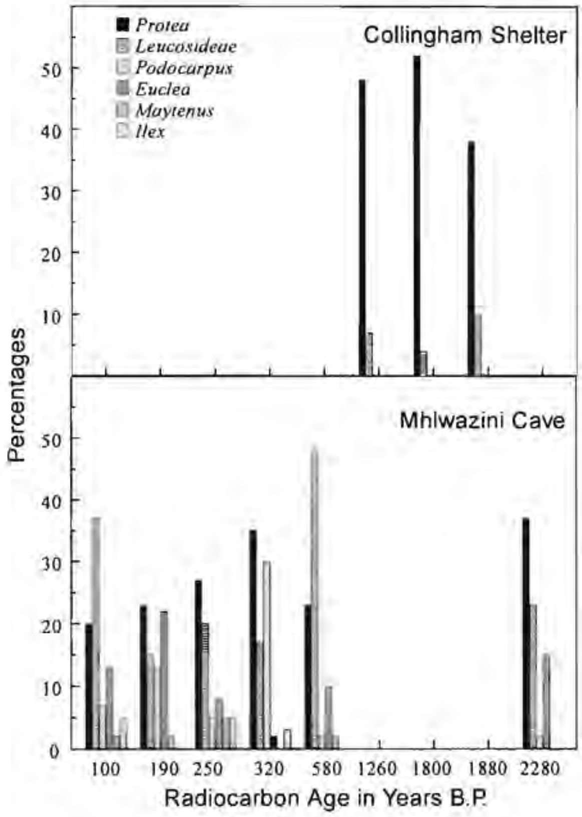

Figure 5. Graph showing percentages of the most common woody species identified from Mhlwazini Cave and Collingham Shelter charcoal assemblages. High percentages of *Protea* and the inverse relationship between *Protea* and *Leucosidea* are discernible. The radiocarbon dates were derived from unidentified charcoal recovered from the archaeological sites.

The most common woody genus represented in the charcoal from both archaeological sites is *Protea* (Fig. 6). The percentages of *Protea* in the charcoal from Mhlwazini Cave do not drop below 20%. At Collingham Shelter these percentages are much higher with the lowest percentage at 63%. There is an inverse relationship between the percentages of *Leucosidea* and *Protea*. The *Euclea/Diospyros* sample also shows some trends inverse to *Protea* but this is not as definitive as that exhibited by *Leucosidea* (Table 1 and Fig. 5).

Discussion

The genus *Protea* has a wide distribution range throughout Africa with, according to Rourke (1980), 13 species in the summer rainfall region of South Africa. Only two of these species occur at Mhlwazini Cave today. On a collecting trip to the area in 1993 one specimen of *P. caffra* and about ten *P. roupelliae* were found to be growing within a 2 km radius of the shelter. Most specimens growing in the area were mature plants growing in sheltered habitats amongst rocks or on very shallow soils. The vegetation at Mhlwazini Cave differs from that of Collingham Shelter in that there is a high percentage of forest margin and precursor shrub forest on the talus slope in the mouth of and for a short distance along the stream bank in front of the cave. The main woody species from this area are *Buddleja salviifolia*, *Carissa bispinosa*, *Diospyros whyteana*, *Euclea natalensis*, *Podocarpus latifolius* and *Rhus tomentosa*. At Mhlwazini Cave today, the amount of dry wood available from this source far exceeds that available from the few *Protea* specimens in the area. This suggests that the decline in *Protea* has continued over the past 100 years even though Mhlwazini Cave is in a nature reserve.

Table 1. Percentages of charcoal from Mhlwazini Cave and Collingham Shelter in the Natal Drakensberg.

Site	Mhlwa	Mhlwa	Mhlwa	Mhlwa	Mhlwa	Colling	Colling	Colling	Mhlwazini
Layer	LSFE F4	MBS D3	BSI E3	BS2 E3	WMAC E3	TBS P5	BSV2	BSV3	AOBS D3
Number of samples	60	60	60	60	60	60	60	60	60
^{14}C Date		190 ± 45		320 ± 40	580 ± 50	1260 ± 50	1800 ± 50	1880 ± 45	2280 ± 50
Laboratory Number		Pta 5102		Pta 4850	Pta 4864	Pta 5408	Pta 5096	Pta 5101	Pta 4868
Protea	20	23	27	35	23	80	87	63	37
Leucosidea	37	15	20	17	48	12	7	17	23
Podocarpus	7	13	5	30	2	0	0	0	2
Euclea/Diospyros	13	22	8	2	10	0	0	0	15
Maytinus	2	2	5	0	2	0	0	0	0
Ilex	5	0	5	3	0	0	0	0	0
Bowkeria	2	13	5	2	2	0	0	0	0
Rhus	2	0	3	5	0	0	2	0	0
Erica	3	0	0	0	0	3	2	7	0
unidentified	5	12	17	5	7	5	0	10	22
unidentifiable	5	0	5	2	7	0	3	3	2

It has been suggested that changes in the relative abundance of woody species represented in the archaeological record result at least partly from human selection in firewood procurement (Prior & Price Williams 1985; February 1992b). According to studies on firewood procurement strategies of contemporary subsistence farmers, people are very specific about the types of woody species they select as fuel wood (Gandar 1982; Milton & Bond 1986). The preference for certain fuel woods over others is linked to the local availability of particular species as well as size, shape, wood hardness and the presence or absence of thorns (Eberhard & Poynton 1987). Other species are avoided for various reasons including superstition (Gandar 1982). Thus high percentages of *Protea* and *Leucosidea* in the archaeological record compared to percentages in the modern environment may be linked to human selection in firewood procurement. A number of researchers have however indicated that despite this apparent bias, past assemblages containing specific indicator species whose ecological susceptibilities are well understood can provide much detailed climatic information (Prior & Price Williams 1985).

Protea roupelliae grows over a wide range of annual rainfall from 760 mm at Suikerbosrand to 1600 mm at Umtamvuna. Within this rainfall gradient there is however an equally wide range in the number of available specimens. At the lower end of the rainfall distribution for the species there are very few specimens (Suikerbosrand) whereas there are large colonies in the higher rainfall areas such as at Gillits (1400 mm) and Umtamvuna. Estimated rainfall for Mhlwazini Cave today is about 850 mm. It is therefore possible that rainfall in the area of Mhlwazini Cave has declined through time and this is manifested in the decline in percentages of *Protea* brought into the cave by people as availability of these plants declined with the decrease in rainfall.

More likely, however, the decline in the *Protea* savannah of the Drakensberg is linked to people rather than climate. The decrease is most evident over the last 300 years at a time when farming intensity in the area increased as agriculturists moved into the Drakensberg foothills (Maggs 1980). This decline in the *Protea* savannah is probably caused by an increase in the number of veld fires in the area surrounding the archaeological sites rather than a decrease in rainfall. At Collingham Shelter the difference between the contemporary environment and the archaeological record is even more striking than at Mhlwazini Cave. Before sedentary farmers first moved into the area more than 60% of the charcoal sample can be identified as *Protea* species. Collingham Shelter is on a private farm managed purely as a cattle ranch. Today there are no *Protea* growing in the immediate vicinity of the archaeological site probably because annual burning is used to enhance the quality of the grazing. Edwards (1967) examined a number of dead or dying *Protea* and concluded that the most common cause of death could be ascribed to a marked increase in veld burning as result of increases in population and settlement of the Tugela basin over the last 100 years. The present evidence indicates that this process began at least 400 years ago when agriculturists first moved into the area.

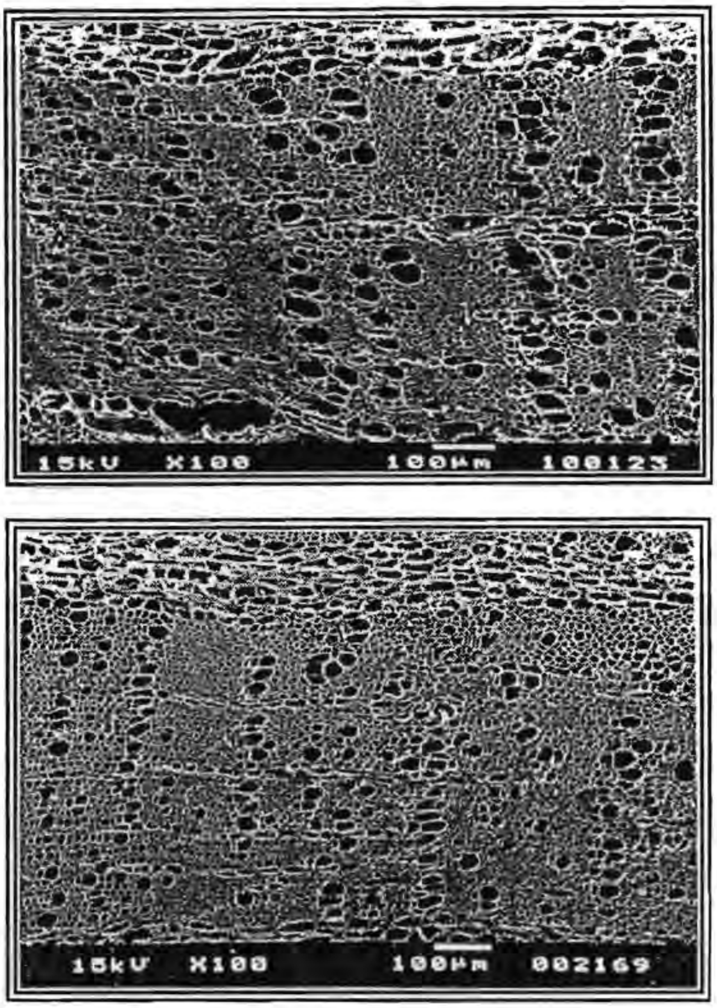

Figure 6. Scanning electron micrographs of *P. roupelliae* charcoal from Collingham Shelter archaeological deposit (top) and a modern analogue collected outside Mhlwazini Cave (bottom). The differences in the diameter of the xylem vessels are clearly visible.

At Umtamvuna Nature Reserve there is a high level of regeneration of *Protea* with many young plants in evidence. Management of this reserve is designed to enhance *Protea* regeneration. Hluhluwe Game Reserve, on the other hand, has a serious bush encroachment problem as a result of which management has been forced towards burning programmes which are specifically designed to counteract this. The result is that there is no *P. roupelliae* in evidence in the reserve today even though Rourke (1980) mentions the Hlabisa area of the Hluhluwe Game Reserve as having the most northerly coastal population of this species. In a neighbouring biome, Bond (1984) and Bond *et al.* (1984) have found that many Cape *Protea* only release stored seeds after fires. As a result, population sizes are sensitive not only to intervals between fires but also to fire season. Whole populations can be destroyed by successive or too frequent winter or spring fires. In the Suikerbosrand reserve in Gauteng, Barlow Kearsley (1989) discovered that the *P. roupelliae* population is faced with extinction mainly because of too frequent fires. She concludes that a fire frequency of about 15 years should ensure the survival of the population.

The results obtained here suggest that the microscopic identification of archaeological charcoal to genus or species level cannot be usefully applied to climate reconstruction because woody species grow under a wide range of environmental conditions. The most common wood type in the archaeological record from both archaeological sites is *Protea roupelliae*. This species grows in variable rainfall from 760 mm at Suikerbosrand through to 1600 mm at Umtamvuna that encompasses any climate change which may have occurred over the last 2000 years.

This method may, however, be useful in determining the anthropogenic impact on the environment. In this respect, the decline in *Protea* toward the present is attributed to an increase in the fire frequency in the area as agriculturists move in circa 400 years ago.

CHAPTER FOUR

RAINFALL RECONSTRUCTION USING VESSEL MORPHOLOGY OF THE WOOD CHARCOAL FROM TWO ARCHAEOLOGICAL SITES

Introduction

The previous Chapter explored the possibility for interpreting climatic and environmental conditions from wood identified by its xylem anatomy. A development of this method is the analysis of xylem vessel size and frequency in charcoal. Measurements on quantitative wood anatomical characters of charcoal may provide climatic information through comparison with the same measurements on an extant sample from areas of known temperature and rainfall (Scholtz 1986; February 1990 & 1992a). This hypothesis is directly based on previous work by Carlquist (1966; 1975; 1977 a & b), Baas (1982) and Baas *et al.* (1983). These studies concluded that in general vessel diameter increases while vessel frequency decreases with increased availability of water.

The advantage of wide vessels to plants is explained by Zimmerman (1978; 1982; 1983). Because hydraulic conductivity is proportional to the sum of the vessel radius raised to the power of four, a slight increase in vessel radius is equivalent to an enormous increase in ability to transport sap. For example, three vessels with relative diameters of 1, 2 and 4 and having cross sectional areas proportional to 1, 4 and 16 will have relative conductivities of 1, 16 and 256. There is, however, a trade-off between increased conductivity and reduced safety. Trees with wide vessels are at far greater risk of serious damage from permanently blocked vessels (vessel embolism) than are those with narrow vessels. The more numerous the vessels, the smaller the chance that the disabling of a given number will seriously affect conduction (Zimmerman, 1983). In order to maximise both water supply and safety, the dimensions and frequency of the conducting units in angiosperm wood vary according to environmental conditions (rainfall and temperature). In times of high rainfall, vessel diameter increases (ability to transport sap) while vessel frequency decreases (degree of safety) with the opposite occurring in times of low rainfall.

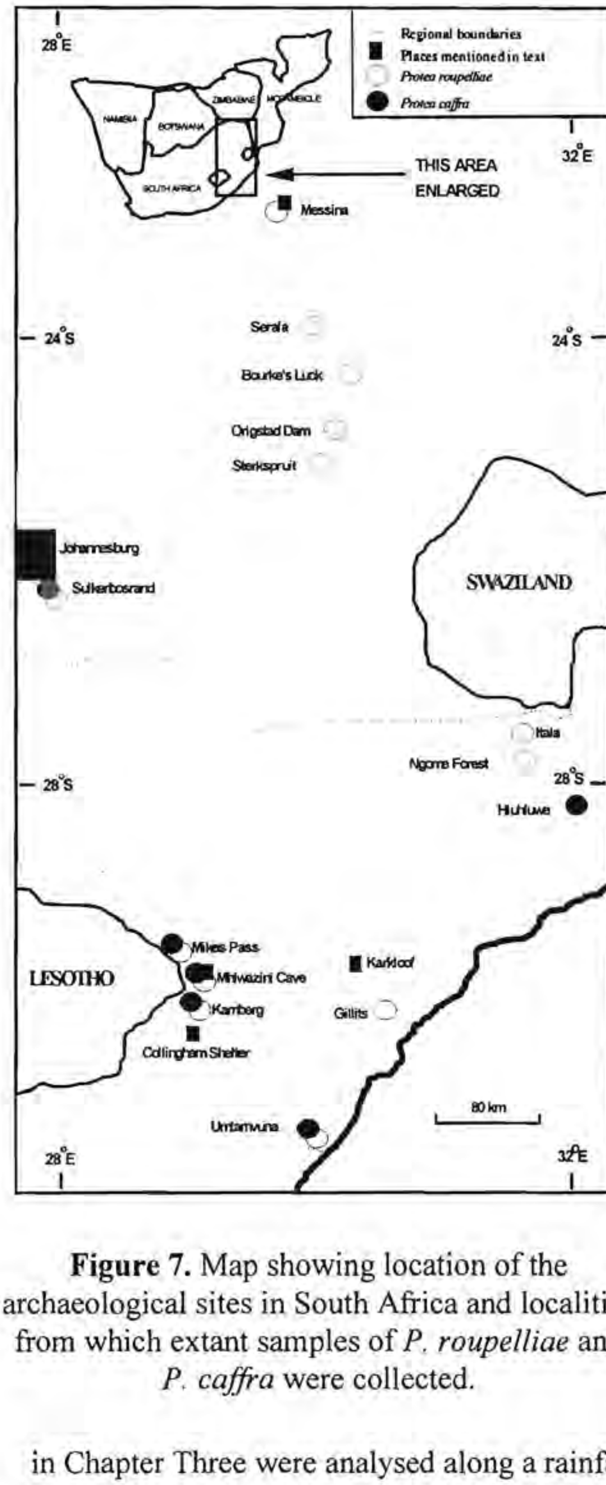

Figure 7. Map showing location of the archaeological sites in South Africa and localities from which extant samples of *P. roupelliae* and *P. caffra* were collected.

A number of studies have examined the association between wood anatomy and climate but none addresses the relationship between specific vessel characteristics and mean annual rainfall. Carlquist (1977b) compared specific wood anatomical variables of the Peneaceae across a wide range of ecological habitats without attempting to obtain actual rainfall figures. Baas and Schweingruber (1987) determined ecological trends for occurrence of certain vessel characteristics along a macro-climatic gradient from boreal through temperate to Mediterranean. Wilkins and Papassotiriou (1989) compared wood samples of *Acacia melanoxylon* from Queensland and Tasmania. Again, this study examined macro-climate rather than a gradient of mean annual rainfall or/and temperature. In order therefore to determine the relationship between vessel diameter, vessel frequency and rainfall a sample of the most common wood types identified in the archaeological charcoal sample in Chapter Three were analysed along a rainfall gradient within the subtropical, summer rainfall region of South Africa (Fig. 7).

For the purposes of this study, the area termed the summer rainfall is that area stretching from Messina on the Zimbabwean border in the north, to Umtamvuna on the Transkei border in the south and from the Indian ocean and Mozambique border in the east to Johannesburg in the west (Fig. 7). The research area from which samples were obtained is focused at Mhlwazini Cave and Collingham Shelter, both at an altitude of 1800 m (6000 ft) in the foothills of the Natal Drakensberg (Fig. 7). These archaeological sites were occupied by hunter-gatherers for 1500 years before agriculturists moved into the area by about A.D. 1600 (Mazel 1990, 1992; Maggs 1980).The most common suitable woody species (*Protea roupelliae*, Chapter Three) identified in the archaeological record was chosen for further analysis to determine relationships between quantitative wood anatomical variables and climate in an extant wood and charcoal sample as well as in the archaeological record.

Methods

Extant wood sample

Within a tree, vessel diameters tend to be greater in roots than in stems, and greater in the stem than in the branches. They also tend to increase with increasing branch diameter (Zimmerman 1978, 1983). In order to control for this variation only similar aged samples from branches with diameters of approximately 2 - 3 cm were collected. These diameters were chosen to reflect the likely firewood gathering strategies of prehistoric people, assuming that firewood was probably not gathered randomly. Instead, pieces are likely to have been selected specifically for ease of transport (February 1992b). The average diameter of branches collected by women in the rural areas of South Africa today is 2 to 4 cm (*pers. obs.*) and it is assumed that the most common dimensions for firewood used by prehistoric people who did not have access to iron would have been similar.

To relate the anatomy of wood to climate, samples have to be collected from undisturbed sites. Roads, buildings and other constructions must be avoided, as increased runoff, as well as watering of domestic plants, affects vessel size and frequency. In order to fulfil these requirements most of the samples were collected in private nature reserves and reserves administered by the Transvaal Provincial Administration or the Natal Parks Board. These reserves are little disturbed by development and generally have good rainfall records. For the purposes of this study rainfall was averaged over four years prior to December 1990 when the samples were collected. Temperature data for the reserves are difficult to obtain since very few of the weather stations close to these reserves collect both rainfall and temperature data.

For this reason temperature was obtained from the computer generated minute by minute data available from the Department of Agricultural Engineering at the University of Natal (Schulze & Maharaj 1993). Measurements of vessel size and number were taken as close to the outer edge of the wood as possible. This would mean that all measurements would be taken on the most recent growth which could be related to the rainfall over the last 4 years. The locations of collected samples are given in Fig. 7 and Table 2.

Table 2. Mean values for tangential vessel diameter and number of vessels for *P. roupelliae* and *P. caffra*. N = Number of samples per locality.

		before carbonisation			after carbonisation		
Locality	Rainfall (mm)	N	Mean Diameter (μm)	Vessel frequency mm^{-2}	N	Mean Diameter (μm)	Vessels frequency mm^{-2}
Protea roupelliae							
Suikerbosrand	765	10	31.8	142.3	5	17.5	352.3
Origstad dam	841	10	29.8	78.9	5	18.7	324.8
Mhlwazini Cave	868	12	28.5	165.6	10	20.3	310.9
Itala N.R.	942	10	30.6	164.0	5	20.5	301.8
Sterkspruit	1005	10	30.6	94.0	5	19.4	265.4
Kamberg N.R.	1105	20	30.5	156.2	5	17.8	383.6
Mikes Pass	1153	6	31.8	124.0	5	19.2	314.4
Gillits	1368	11	38.9	78.8	5	25.2	83.4
Ngome Forest	1410	9	36.4	104.2	5	21.5	140.3
Bourkes Luck	1411	10	33.6	106.1	5	20.0	320.0
Serala	1600	8	37.7	85.6	5	22.2	154.0
Umtamvuna	1664	15	42.6	64.5	5	25.0	147.8
Correlation coefficient (R)			0.88	-0.62		0.74	-0.73
Probability (P)			0.0001	0.03		0.005	0.007
Protea caffra							
Oog van Male.	546	4	39.0	53.2			
Suikerbosrand	765	10	35.7	89.2	5	46.2	166.2
Kamberg N.R.	1105	10	44.4	55.0	5	54.6	82.6
Mikes Pass	1153	9	39.1	54.2	5	44.7	161.5
Hluhluwe N.R.	1170	10	45.8	44.5	5	61.7	95.2
Umtamvuna	1664	10	49.7	56.1	5	60.1	94.3
Correlation coefficient (R)			0.82	-0.33		0.62	-0.56
Probability (P)			0.04	NS		NS	NS

In the laboratory a 2 cm thick disk was cut off the end of each piece of wood and split into sections about 5 - 8 mm wide incorporating both the pith and the cambium. Prior to microscopic examination, the wood was softened by boiling before samples were cut in transverse section at thicknesses between 25 and 30 μm using a Reichert Jung (Vienna, Austria) base sledge microtome. The thin sections were stained over two days in a mixture of alcohol, glycerol and safrinin red, mounted in Kaisers gelatine and glycerine on glass microscope slides and photographed in transverse section at a magnification of 40x using a Leitz (Wetzlar, Germany) Laborlux K incident light microscope. A graticule was also photographed at the same magnification so that magnifications could be calculated when the photographs were developed and printed. Measurements of vessel size and number were then made using a custom written computer programme linked to a Summagraphics (Fairfield, U.S.A.) digitising tablet. Diameters were measured for a maximum of 50 vessels per section of wood at the widest part of the opening and excluding the cell wall (IAWA Committee 1989). In this study both tangential and radial vessel diameters were measured because both values are needed to calculate vessel area. Using these diameters, the computer programme applies the area formula for an ellipse to calculate vessel area for each vessel. Total vessel area for the section is measured by means of a point count, the rationale and methodology of which is well documented (e.g. Clark 1982). A plastic sheet marked out in a 10 mm-square grid was placed over the photographic image to be digitised in order to allow total vessel area to be counted using the number of point intersects. Mean vessel area was then calculated by dividing the sum of the areas of the measured vessels by the number of vessels measured. Mean vessel area was then divided into the total vessel area to obtain a figure for the number of vessels per square millimetre.

Extant wood charcoal sample

To make direct comparisons between the modern and archaeological samples it is necessary to first char the modern material. This is because wood shrinks with carbonisation. Because of this, shrinkage formulae developed from fresh wood morphology cannot be applied directly to charcoal. The shrinkages accompanying carbonisation are considered to be uniform, as the ratio between cell diameter and cell wall thickness does not change during pyrolysis (McGinnes *et al.* 1971). What changes is the cell diameter and therefore the number of vessels in a given area. From the shrinkage factors produced by Beall *et al.* (1974), Cousins (1975) calculated this increase in vessel frequency to be as much as a doubling of cells in a given cross section of the original wood. The relationship between the numbers of cells in fresh and charred wood of the relevant species must be determined before evidence from archaeological charcoal samples can be interpreted.

To ascertain the relationship between rainfall, vessel diameter and vessel frequency in charred wood along a climate gradient some of the fresh wood samples were charred as described in Chapter Three and re-analysed. Five samples per collecting site were chosen for analysis. To simulate the natural situation as closely as possible the samples were air dried for eight months before charring. A JEOL JSM 5200 scanning electron microscope (SEM) was used for photography. Charring and preparation for scanning electron microscopy were the same as described above for incident light microscopy (Chapter Three). In the case of the SEM, fragments were mounted on aluminium stubs, vacuum desiccated and then gold sputter coated. As with the fresh wood sample measurements of vessel size and number were then made using the custom written computer programme linked to a Summagraphics digitising tablet.

Table 3. Mean values for tangential vessel diameter and number of vessels for *P. roupelliae* from the archaeological sites Mhlwazini Cave and Collingham Shelter. N = Number of samples from each layer, R.C. = Radiocarbon and Layer = excavated archaeological unit.

Locality	N	R.C. Age (yr. B.P.)	R.C. Lab. number	Layer	Mean (μm)	Vessels /mm^2
Mhlwazini	10	Modern		MOD	20.3	310.9
Mhlwazini	15	190	Pta 5102	MBS	24.5	224.0
Mhlwazini	18	320	Pta 4850	BS2	23.9	227.2
Mhlwazini	14	580	Pta 4864	WMAC	24.0	208.9
Collingham	25	1260	Pta 5408	TBS	22.4	152.7
Collingham	26	1800	Pta 5096	BSV2	24.0	249.9
Collingham	27	1880	Pta 5101	BSV3	23.3	257.2
Mhlwazini	14	2280	Pta 4868	AOBS	25.1	314.6

Archaeological charcoal sample

The archaeological charcoal samples were prepared for microscopy by physical fracture as described in Chapter Three. As many samples as possible were analysed (Table 3). The SEM was used for all photography. Measurements of vessel size and number were taken closest to the outer edge of the charcoal piece in exactly the same way as described for the freshwood sample.

Results

Identification

At Mhlwazini Cave *Protea* spp. comprise 27.5% of the woody species in the charcoal sample, *Leucosidea* sp. 26.5% and *Podocarpus* spp. 10%. At Collingham Shelter *Protea* spp. forms 76% of the charcoal and *Leucosidea* sp. 12% (Table 1). A more detailed analysis of the identification of this charcoal is given in Chapter Three.

Table 4. Description of the anatomy of the two species of *Protea* based on an examination of 132 *P. roupelliae* and 55 *P. caffra* specimens.

	P. roupelliae	***P. caffra***
Growth Rings	Indistinct to distinct. Diffuse porous to ring porous.	Indistinct. Vessels occasionally arranged tangentially.
Vessels	Solitary and often tangentially arranged. Larger vessels 40 - 65 µm in diameter. Between 65 - 165 vessels per mm^2. Vessel element length not measured. Perforation plates simple. Intervessel pitting alternate. no spiral thickening.	Solitary diffuse porous can be tangentially arranged. Larger vessels 55 - 85 µm in diameter. Between 45 - 90 vessels per mm^2. Vessel element length not measured. Perforation plates simple. Intervessel pitting alternate. no spiral thickening.
Fibres	Thick walled.	Thick walled.
Parenchyma	Axial parenchyma unilateral paratracheal.	Axial parenchyma predominantly paratracheal. Can be unilaterally paratracheal.
Rays	Rays of two distinct size classes. Smaller rays 1 - 3 cells wide. Larger rays 4 - 10 cells wide in tangential section. Ray height greater than 1 mm and seldom more than 3 mm. In transverse section larger rays often herring bone pattern as ray cells can be rhomboidal. Average ray area in transverse section 20% of total area measured.	Two distinct size classes. Smaller rays 1 - 3 cells wide. Larger rays 4 - 10 cells wide in tangential section. Ray height greater than 1 mm

Leucosidea sericea is the most common species of *Leucosidea* in the Natal Drakensberg today. Unfortunately, it only grows along stream banks and its distribution range is restricted to a specific altitude in the Drakensberg. This combination of restricted distribution and proximity to water makes it unsuitable as a species for determining changes in xylem anatomy related to climate. It was therefore not considered further. *Protea roupelliae* and *Protea caffra* are the most common *Protea* spp. in the research area today. These two species grow over a wide range of ecoclimatic regimes within the summer rainfall region and occur in the vicinity of the archaeological sites under investigation. *Protea roupelliae* and *Protea caffra* were therefore chosen for further analysis. So as to positively identify the *Protea* species from the charcoal in archaeological sites the anatomical structure of the wood has to be recognised (Table 4). The descriptions presented above are based on an examination of 132 *P. roupelliae* and 55 *P. caffra* specimens (Table 4). With no *Protea* growing in the vicinity of Collingham Shelter, it is impossible to compare the generalised anatomy of either *P. roupelliae* or *P. caffra* with that of corresponding specimens which could have grown in the vicinity of the shelter. Only *P. roupelliae* can be compared anatomically with samples from the vicinity of Mhlwazini Cave, where one growing specimen of *P. caffra* was encountered (Table 2).

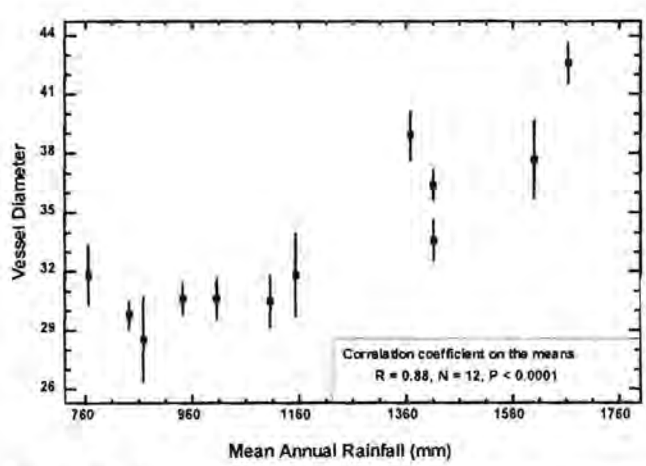

Figure 8. Means and standard errors for tangential vessel diameter (µm) of an extant sample of *P. roupelliae* along a rainfall gradient in the summer rainfall region of South Africa.

Xylem Analysis

Extant wood sample

In *P. roupelliae* and *P. caffra* the relationship between xylem morphology and rainfall is in accordance with the findings of previous studies (Carlquist 1966; 1977a; 1977b; Baas *et al.* 1983; Zhang *et al.* 1988; Wilkins & Papassotiriou 1989). Those plants growing in wet environments have larger and fewer vessels than conspecifics growing in more xeric environments (Table 2, Fig. 8). Correlation analysis shows a very strong relationship between mean vessel diameter and rainfall for *P. roupelliae* (N = 12, R = 0.88, P <0.0001, Fig. 8) and *P. caffra* (N = 6, R = 0.82, P < 0.04). There are also reasonable correlations between rainfall and vessel frequency (*P. roupelliae:* N = 12, R = -0.61, P <0.05, *P. caffra:* N = 6, R = -0.33, P >0.05, NS, Table 2).

Extant wood charcoal sample

Mean values of vessel diameter and vessel frequencies for charred wood are substantially different from those for fresh wood. Shrinkage in tangential vessel diameter compares well with that quoted in McGinnes *et al.* (1971) with an average shrinkage of 38% for *P. roupelliae* and 42% for *P. caffra* on conversion from wood to charcoal. The results for both *Protea* species confirm Cousins's (1975) findings that on average the value for vessel frequency is almost doubled in the conversion from wood to charcoal (Table 2). Charred samples of *P. roupelliae* show a significant correlation (P<0.005) between rainfall and mean vessel diameter (Table 2, Fig. 9). The results for *P. caffra* are not significant probably because of the small sample size (Table 2). Mean values for vessel diameter of *Protea caffra* are lower than those for *Protea roupelliae*.

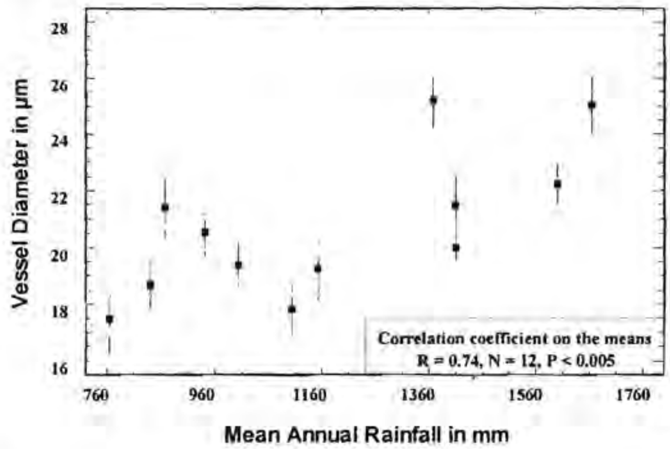

Figure 9. Means and standard errors for tangential vessel diameter (µm) of an extant sample of *Protea roupelliae* (after carbonisation) along a rainfall gradient in the summer rainfall region of South Africa.

Differences between charred samples of the two species of *Protea* are in tangential vessel diameter (mean values for *P. caffra* 24.8 µm and *P. roupelliae* 20.6 µm) and in number of vessels (mean values for *P. caffra* 120 per mm^2 and *P. roupelliae* 258 per mm^2). Within a normal distribution, however, the two ranges unfortunately overlap making it extremely difficult to quantify the differences between *P. caffra* and *P. roupelliae* on vessel morphology alone. As ray height of *P. roupelliae* seldom exceeds 3 mm but often does so in *P. caffra*, ray height was considered a reasonable defining feature, although there is still some overlap between the two species.

Archaeological charcoal

Results for tangential vessel diameter of the *Protea* samples from Mhlwazini Cave and Collingham Shelter indicate that vessels were larger at 2300 B.P. decreasing in size to 1300 B.P. then increasing again somewhat to 200 B.P. before decreasing to the present sizes (Table 3 and Fig. 10). This suggests that there was a general decrease in rainfall from 2300 B.P. to the present but with a slight counter trend of increased rainfall between 600 B.P. and 200 B.P. (Table 3 and Fig. 10).

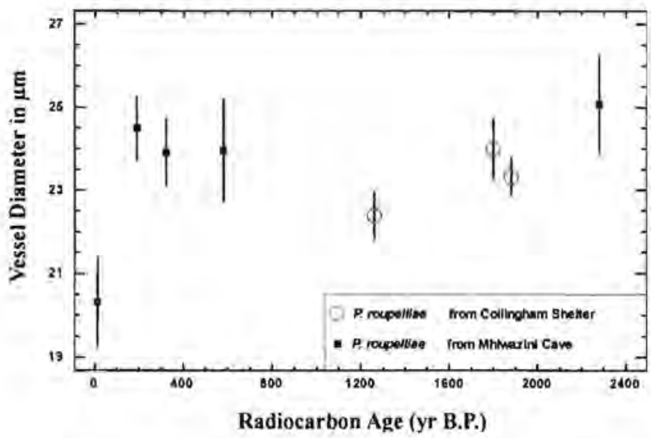

Figure 10. Means and standard errors for tangential vessel diameter (in µm) of an archaeological charcoal sample of *P. roupelliae* from Mhlwazini Cave and Collingham Shelter

Discussion

Both Collingham Shelter and Mhlwazini Cave are located at similar altitudes in the *Protea* Savannah belt of the Drakensberg with similar mean annual rainfall and temperature regimes. Mhlwazini Cave is well screened by afromontane forest vegetation to which the inhabitants would have had access as a fuel source. The hunter-gatherers who occupied the cave would also have had access to the *Protea* shrubs as well as the mountain *Podocarpus* forest. All of these species are evident in the archaeological record (see Chapter Three, Table 1). At Collingham Shelter today there are no *Protea* species growing in the immediate vicinity of the archaeological site. Yet more than 70% of the charcoal from three levels can be identified as *Protea* spp (Fig. 5). The reason for the difference between the archaeological record and the modern environment is thought to be veld management practice rather than climate change. (Chapter Three). Xylem analysis of the archaeological charcoal, however, shows that when farming communities first moved into the Drakensberg circa 400 years ago rainfall was much higher than at present. While burning programmes may be the major contributor toward declining *Protea* savannah in the Drakensberg mountains, the decline in rainfall over the last 400 years for this region may well be a contributing factor.

Significant correlations (Table 2, Fig. 9) between rainfall and tangential vessel diameter for a charred sample of *Protea roupelliae* (collected along a rainfall gradient) suggest that such measurements on an archaeological charcoal sample may be used to reconstruct rainfall patterns through time. The results of these measurements from Collingham Shelter and Mhlwazini Cave reinforce and expand the little evidence there is for rainfall change in South Africa.

It would appear from the work of Butzer *et al.* (1978), Klein (1980), Butzer (1984) and Cooke and Verstappen (1984) that at about 3000 B.P. conditions in the summer rainfall region were much wetter than at present (Tyson 1986). In addition, Smith's (1992) tentative suggestion of a single flood event of the Orange River dated to about 2400 B.P. coincides with a wetter period identified at Mhlwazini Cave in the present study (Chapter Two). Tyson (1986) and Tyson and Lindsay (1992) suggest that the period prior to 1850 was relatively dry. With climate amelioration at about A.D. 1850 (100 B.P.) warming occurred and summer rainfall increased (Tyson & Lindsay 1992). Much of the evidence for a drier and cooler Little Ice Age is derived from a reinterpretation of the few tree ring records available for South Africa (Hall 1976; Dunwiddie & La Marche 1980) by Tyson (1986). The present data, however, contradicts what little evidence there is suggesting that the period prior to 1850 was relatively dry. Rather, it appears that there is a general decrease in rainfall from 2300 B.P. to the present with a slightly wetter period during the Little Ice Age (Fig. 10). The results show present conditions to be much drier than at any other time within the last 2000 years (Fig. 10).

The techniques described here are not only useful in determining patterns in rainfall but may also be useful in determining actual rainfall figures. The significant correlation between tangential vessel diameter of a charred sample of *Protea roupelliae* and rainfall (Table 2, Fig. 9) suggests that rainfall at Mhlwazini Cave has been substantially higher in the past (*ca* 1300 mm to *ca* 1600 mm) than it is at present (*ca* 900 mm). It is only at 1200 B.P. that this figure (*ca* 1200 mm) approaches contemporary values (Fig. 10).

Since there are abundant assemblages of charcoal from archaeological sites, the only limitations on this method of obtaining proxy rainfall data are the resolution of the radiocarbon dates and a suitable distribution of sites. The resolution of the time series is, however, insufficient to allow detailed interpretation of rainfall fluctuations over the last 2000 years. This is because the calculated radiocarbon age of a sample does not compare directly with the actual age of that sample. The calculation of the radiocarbon age of a sample assumes that the levels of ^{14}C in the atmosphere have been constant. This is, however, not the case as the ^{14}C activity in the atmosphere has varied through time. With this range in atmospheric levels of ^{14}C comes a range in radiocarbon ages. It is possible to calibrate for this range in radiocarbon ages by measuring the radiocarbon ages of tree rings of known age (Atwater, Stuiver & Yamaguchi 1991). This calibration has been achieved for most of the Northern Hemisphere. It is assumed that the ^{14}C activity in the atmosphere is constant around the world so that it is possible to use the North American dendrochronological calibration curve in South Africa. The calibration curve is not a uniform smooth curve but has a number of plateaux, peaks and troughs. Thus a sample with a radiocarbon age of 152 ±30 B.P. could calibrate to anywhere between 1650 A.D. and 1955 A.D., a range of 300 years (Atwater, Stuiver & Yamaguchi 1991). On the other hand a sample with a radiocarbon age of 500 ±20 B.P. would calibrate to 1427 ±12 A.D. Note that in this case the standard deviation has decreased. The accuracy of the radiocarbon date depends very largely on where it falls on the curve. For example any sample from the last 300 years will not give a very accurate result because of the nature of the curve. Therefore, the two samples dated to 190 B.P. and 320 B.P. (Fig. 10) may even be modern which could invalidate some of the earlier discussion with reference to the Little Ice Age. The results for this study should therefore be treated with caution until confirmed through replication from more locations and species. Radiocarbon dating is nonetheless very important so as to place a set of archaeological assemblages within a specific age group. Proxy rainfall records obtained from dendrochronology can be used to verify those records obtained from radiocarbon dated samples (such as from the charcoal analysed in this Chapter).

CHAPTER FIVE

AN ASSESSMENT OF THE DENDROCHRONOLOGICAL POTENTIAL OF TWO *PODOCARPUS* SPECIES

Introduction

In the previous chapter results of measures on archaeological charcoal samples reinforce and expand on the little evidence there is for rainfall change over the last 2000 years in the summer rainfall region of South Africa. The resolution of the time series based on radiocarbon dates does not, however, allow for the type of analysis central to this thesis which is to fulfil the need for a high resolution rainfall index that extends back in time for more than 100 years. Tree rings and ice cores have demonstrated the capacity to produce such records. This essentially leaves tree rings since ice cores are not readily available in the temperate south latitudes except for Antarctica and the high Andes. Within South Africa Dunwiddie and La Marche (1980) demonstrated the potential for using *Widdringtonia cedarbergensis* and Curtis *et al.* (1978) gave some evidence for the dendrochronological potential of *Podocarpus falcatus*. These initially promising results were however never fully exploited.

Dendrochronology in the Northern Hemisphere provides a good climate record going back in time for thousands of years (Ferguson 1969; Hillam *et al.* 1990) but of the vast number of tree species in South Africa, few have dendrochronological potential. Lilly's (1977) assessment of 108 indigenous South African trees identified the *Podocarpus* and *Widdringtonia* species as having potential for dendrochronology. It was this research effort along with that described by Hall (1976) for a single *Podocarpus falcatus* specimen from Karkloof in Kwazulu/Natal that directed the focus for tree ring research in South Africa on *Podocarpus* and *Widdringtonia* species (McNaughton 1978; Curtis *et al.* 1978; McNaughton & Tyson 1979; Dunwiddie & La Marche 1980; Tyson 1986).

Basic to dendrochronology is the assignment of each consecutive annual ring to the year in which it was formed. Inward from the precisely dated outermost ring successive growth rings are assigned to sequential years. Variations in the width of these rings due to climatic factors form the basis for cross-matching or cross-dating among specimens from the same locality (Fritts 1967, 1976). Marker years with exceptional divergence in ring width are matched up within a tree and between trees to corroborate the initial dating. After cross-dating the ring width measures of a number of specimens from the same locality exhibiting the same patterns in the width of these rings are combined to develop a chronology. In dendroclimatology this chronology is related to available regional temperature and precipitation records to form the basis for climate reconstruction.

The principle that apical and radial growth results in the formation of an annual ring is, however, not a biological certainty since previous research (Curtis *et al.* 1978) has indicated that ring counts in *Podocarpus* do not always correspond to the age of the tree because of the tendency for rings to merge and show discontinuities. Curtis *et al.* (1978) point out that only by felling the tree and working with whole trunk cross sections is age determination based on growth ring analysis feasible in *Podocarpus* species. With *Protea* species, such as *P. roupelliae*, even this method does not produce positive results because ring definition is not clearly defined. No dendrochronological study using South African *Podocarpus* species moves beyond the work of Curtis *et al.* (1978) nor does any study test their hypothesis. McNaughton and Tyson (1979) used their methods (Curtis *et al.* 1978) to make some statements on climate from 12 trees from the Witelsbos forest in the southern Cape, as did Geldenhuys (1994) to determine the age of specific *Podocarpus falcatus* specimens. There is, however, no mention in these studies of either developing a chronology or of cross-dating the trees.

Figure 11. Map showing the location from which samples of *P. falcatus* and *P. latifolius* were collected.

Curtis *et al's* (1978) results are based on five, six year old *Podocarpus henkelii* trees and a single *P. falcatus* specimen. A sample size such as this is too small to provide a statistically significant result (Fritts 1976). Using eight *P. latifolius* and six *P. falcatus* specimens of known age this section of the thesis re-evaluates the methods developed by Curtis *et al.* (1978) while it also examines the potential for using ring width measures of *Podocarpus* in the two fundamentals of dendrochronology; cross-dating and chronology development.

Methods

Eight whole trunk cross sections of *P. latifolius* and six of *P. falcatus* were obtained from trees located at 340m elevation at Harkerville (34°03' : 23°14') near Knysna on the south coast of South Africa (Fig. 11). Age of the trees was determined by counting branch whorls, an accepted method used by the local foresters to date young *Podocarpus* trees. The trees were growing on deep, well drained soils derived from stabilised but unconsolidated dune sands comprising medium to coarse, well sorted quartz grains. Rainfall is non-seasonal with average annual amounts between 700 and 800 mm. Specimens were felled as close to the ground as possible so that the maximum possible age of the trees could be incorporated into the cross section. The initial sample size here is much smaller than the 20 or more trees recommended by Fritts (1976). This was, however, the maximum number of trees that could be cut down since *Podocarpus* spp. are rare and endangered.

Table 5. Relationship between known age (years) and ring count age (rings) for *P. latifolius* and *P. falcatus*.

Spec. num.	Height (m)	Age (years)	Age (rings)	% error
P. latifolius				
2620	1.5	14	18	22.2
2617	2.6	18	24	25
2615	2.1	19	24	20.8
2619	2.1	21	23	8.7
2613	2.7	23	24	4.2
2618	2.1	25	33	24.24
2614	2.8	26	30	13.3
2616	2.6	26	32	18.8
P. falcatus				
2624	1.2	12	26	53.84
2621	1.3	15	12	20.00
2623	2.2	19	16	15.78
2622	2.5	23	24	4.16
2626	3.0	23	23	0
2625	3.1	29	24	17.24

In the laboratory, a belt sander (Makita 4" Japan) was used to prepare the specimens for microscopy starting with 60 grit paper and using progressively finer paper finally finishing with 400 grit. Ages of the trees were then determined using the technique proposed by Curtis *et al.* (1978), *i.e.* the circumference of each ring was traced as carefully as possible using a Wild M3C stereo microscope. After the ages were determined ring widths were measured on two radii of each section using a Wild M3C stereo microscope linked to the computerised image analysis programme FIPS (CSIR Pretoria). After manually matching the ring width variations among trees of the same species so as to identify the exact year in which each ring was formed (cross - date), the computer programme COFECHA (Holmes, 1983) was used to identify problems in measurement and to verify cross-dating. This programme allows for computer assisted quality control of the dating and measurements of the original indices. The software develops a master dating series and then compares each individual tree ring measurement index to that series.

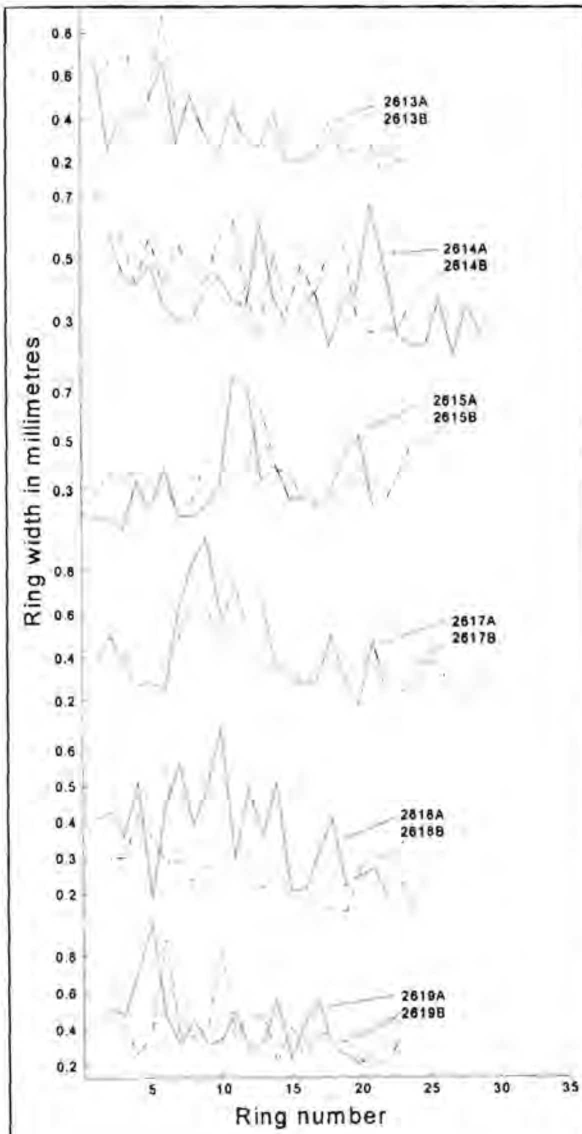

Figure 12. Ring width measures for two radii per tree from each of six of the *P. latifolius* specimens analysed illustrating lack of cross-dating within the same tree as well as between different trees.

Results

Percentage error between known age and ring count age for both *P. latifolius* and *P. falcatus* were much higher than expected, ranging from 0% to 25% (Table 5). The ring structure of only one specimen was such that no estimate of age could be arrived at. One other tree had a very high percentage error (54%) which may be attributed to an error in the whorl count. Of the eight samples of *P. falcatus* and six of *P. latifolius* examined, it was only possible to determine a pattern of wide and narrow rings common to two radii (cross-date) from one *P. falcatus* (number 2618, Table 5) and one *P. latifolius* (number 2625, Table 5) with any degree of certainty. It was not possible to cross-date any of the other trees within themselves (Fig. 12 & Fig.13). Cross-dating of the 28 radii from 14 trees was not possible either among specimens of the same species or between species (Figs. 12 & 13). Use of the computer programme COFECHA (Holmes 1983) did not improve the results.

Discussion

For too long now, the focus for dendrochronology in South Africa has been on *Podocarpus falcatus* or *Podocarpus latifolius*. The results of the present study indicate that this position is untenable. Dendrochronological research in South Africa should not focus solely on *Podocarpus* species, but should diversify, developing new methods and ideas with new species. The results obtained in this study suggest that *Podocarpus falcatus* and *Podocarpus latifolius* are unsuitable for determining a methodology for dating, cross-dating and chronology development, all of which are fundamental to dendrochronology and climate reconstruction from tree rings (Fritts, 1976). The results indicate that even though whole trunk cross sections were used, as advocated by Curtis *et al.* (1978), there is still a large percentage of error when calculating the age of these trees from ring counts. Furthermore, even if this percentage error was smaller a combination of poorly defined, locally absent and converging rings makes cross-dating between different trees from the same locality an impossible task. Cross-dating within the same tree was almost as difficult only being possible in one *P. falcatus* and one *P. latifolius*. These results

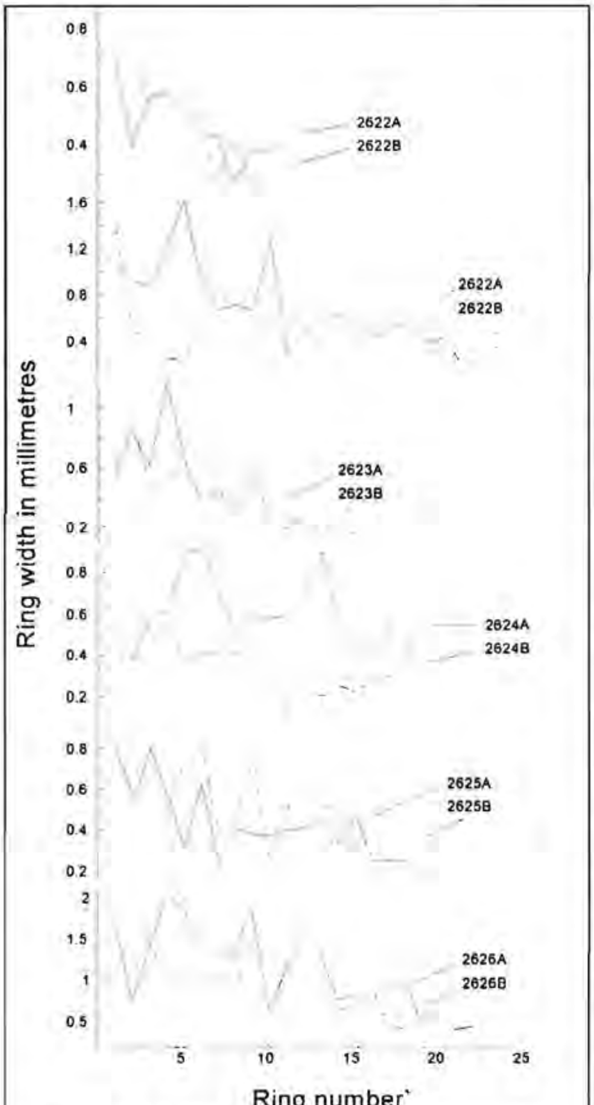

Figure 13. Ring width measures for two radii per tree for each of the *P. falcatus* specimens analysed illustrating lack of cross-dating within the same tree as well as between trees.

suggest that because of locally absent and converging rings future dendrochronological research using *Podocarpus* from the wetter parts of South Africa is not justifiable, especially since whole trunk cross sections have to be used in the analysis and *Podocarpus* are rare and endangered. It is possible that trees obtained from a drier environment such as the Northern and North-West Provinces or the west coast of South Africa may exhibit some attributes which can be used in chronology development. Any future research should focus on cross-dating and chronology development from trees collected from the drier parts of South Africa as it has been shown that in the drier areas, where moisture stress is greatest, the climate signal within the ring series is enhanced (Fritts 1967).

Dunwiddie and La Marche (1980) have previously identified the dendrochronological potential of *Widdringtonia cedarbergensis*. This species grows in the Cedarberg Mountains of the Western Cape Province, a location which should be ideal for dendrochronology because rainfall is severely limited during the hot summers. It is therefore possible that chronologies developed from *Widdringtonia cedarbergensis* will have significant correlations with rainfall. Dunwiddie and La Marche (1980) did not, however, find conclusive correlations between their tree ring chronology and rainfall. The next chapter of this thesis re-evaluates the dendrochronological potential of *Widdringtonia cedarbergensis* with the objective of obtaining direct correlations between ring width indices and rainfall.

CHAPTER SIX

THE RELATIONSHIP BETWEEN RING WIDTH MEASURES AND PRECIPITATION FOR *WIDDRINGTONIA CEDARBERGENSIS*

Introduction

The Southern Hemisphere has very few available instrumental and historical climate records when compared to the Northern Hemisphere and South Africa has no high resolution climate series that extends back in time for more than 100 years. Tree ring records from South America have proved useful for almost 4000 years of temperature and precipitation reconstruction (Lara & Villalba 1993) and similar results have been recorded from Tasmania (Cook *et al.* 1992) and New Zealand (Norton *et al.* 1989). As has been illustrated in the previous chapter, South Africa presents more problems in the application of dendrochronological studies than any other region in the Southern Hemisphere, primarily because of poorly defined, locally absent and converging rings. These problems have been dealt with extensively in the publications of the Climatology Research Group at the University of Witwatersrand (Lilly 1977; Curtis *et al.* 1978; McNaughton & Tyson 1979; Dyer 1982; Tyson 1986).

The work of the Climatology Research Group especially that of Lilly (1977) has, however, focused dendrochronological research in South Africa on two species of *Podocarpus*. As a result of this research there has been very little progress in finding species that are more suitable for denrochronology. Dunwiddie and La Marche (1980) have successfully developed a chronology for *Widdringtonia cedarbergensis*. This chronology at a site called Die Bos, in the Cedarberg Mountains near Cape Town (Fig. 14), is the only dated annual ring width chronology available for a South African indigenous species. However, Dunwiddie and La Marche (1980) were not able to establish a direct correlation between their ring width index chronology and rainfall or temperature. Rather, they could only tentatively interpret their chronology as a record of spring and early summer moisture availability. In a re-evaluation of the Dunwiddie and La Marche (1980) data set, Zucchini and Hiemstra (1983) concluded that although significant at the 1 % level the correlation between the transformed ring width indices and rainfall records from the nearest weather station at Wupperthal was not sufficient to reconstruct rainfall patterns since only 22% of the variability in transformed ring width indices could be attributed to rainfall.

Following Zucchini and Hiemstra's (1983) conclusion that a rain gauge closer to the Die Bos site may well have resulted in a better correlation, the research described in this chapter uses *W. cedarbergensis* from separate localities in the Cedarberg which were specifically chosen because of their proximity to rainfall stations. The results of the present study should therefore indicate whether a ring width index chronology of *W. cedarbergensis* can be used in climate reconstruction in southern Africa.

Methods

In accordance with the suggestion by Zucchini and Hiemstra (1983) the trees selected for this study were situated close to a rain gauge. Rainfall records for Algeria are available from 1900 to 1994 and are collected approximately 1500 m from the location of the trees. The nearest reasonable rainfall record to Krakadouw is located approximately 5 km away, at Wupperthal, with data available from 1898 to September 1977. These two data sets are ideally situated to explore more fully the relationship between ring width index chronologies of *W. cedarbergensis* and rainfall.

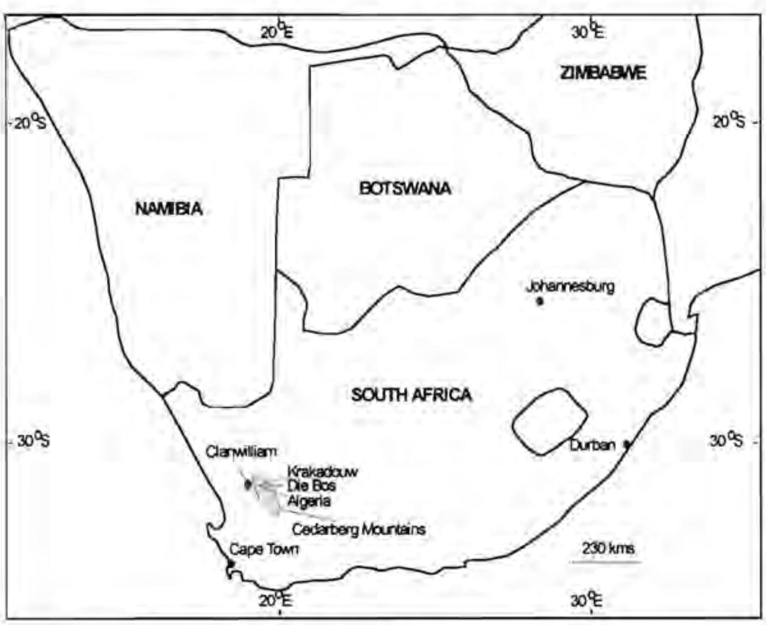

Figure 14. Map showing the location of the Cedarberg Mountains in South Africa and the sites from which samples of *W. cedarbergensis* were collected.

Increment borer samples of *W. cedarbergensis* were collected in February 1995 from 10 trees at Algeria (32° 22' : 19° 04') in the southern Cedarberg and 12 trees at Krakadouw (32° 13' : 19° 04') in the northern Cedarberg (Fig. 14). At Algeria these samples were supplemented by a further 5 radial discs cut from living trees in May 1995 as well as 11 discs collected by La Marche and Dunwiddie in 1976 and 1978. Radial cross sections were also collected from 9 trees killed in a fire at the Krakadouw site in January of 1995. The Algeria sample came from a plantation that had been planted circa 1910 at an altitude of 600 m in the southern Cedarberg, while the Krakadouw sample had been planted circa 1900 in the northern Cedarberg at an altitude of 1000m. The climate at these sites is classified as Mediterranean with definite winter rainfall between June and August of between 500 and 900 mm at Algeria and 200 to 300 mm at Krakadouw. Summers are hot and dry with rainfall averaging around 20 mm at Algeria and 5 mm at Krakadouw. The distance between the two sites, as the crow flies, is approximately 17 km. Clanwilliam which is approximately 26 km from Algeria and 15 km from Krakadouw at an altitude of 152 m has a mean maximum temperature of 27°C and minimum of 12°C.

In the laboratory a belt sander (4" Makita, Japan) was used to prepare the surface of the cores and discs for microscopy. Ring widths were measured with a computer linked (Bannister model, America) Henson incremental measurement machine in conjunction with a Bausch and Lomb (Germany) stereoscopic microscope with cross hairs, normally at 15X to 30X magnification (Robinson & Evans 1980). Cross-dating following the technique described by Stokes and Smiley (1968) was extremely difficult and not always successful. As a result, a refinement on this technique was adopted, whereby rings were first measured and then cross-dating was verified and corrected with the computer programme COFECHA (Holmes 1983) as described in the previous chapter. All anomalies are flagged so that these can be re-examined or re-measured to ascertain the nature of the problem.

Cross-dated series were selected for high sensitivity and high correlation with the adjusted master series. The computer programme ARSTAN (Cook 1985) was used to develop a chronology from each of the two localities. Ring widths were de-trended into dimensionless indices to remove the effects of changes in tree growth that result from ageing as well as to homogenise the mean and variance and to produce a standard chronology for the site suitable for climate reconstruction (Cook 1985). Climatic interpretation of the two chronologies was based on the relationship between ring width indices and available regional precipitation records for the rainfall stations at Algeria and Wupperthal. These relations were investigated using correlation functions for various combinations of monthly and seasonal precipitation from 1919 to 1994 for Algeria and from 1898 to 1977 for Krakadouw.

Results

Of the 24 cores and 9 discs (21 trees) from Krakadouw only 22 radii (17 radii from discs and 5 from cores) from 11 trees were successfully cross-dated (Fig. 15 illustrates cross-dating). The oldest tree at Krakadouw was 99 years old which is very close to the approximate date of planting, 1898. Of the 16 discs and 20 cores (26 trees) collected from Algeria only 25 radii (19 radii from discs and 6 from cores) from 14 trees were successfully cross-dated. The oldest trees at Algeria date to 1918/1919. It is possible that about 4 years of growth are missing from the collected discs indicating a good correlation between actual age and ring count age.

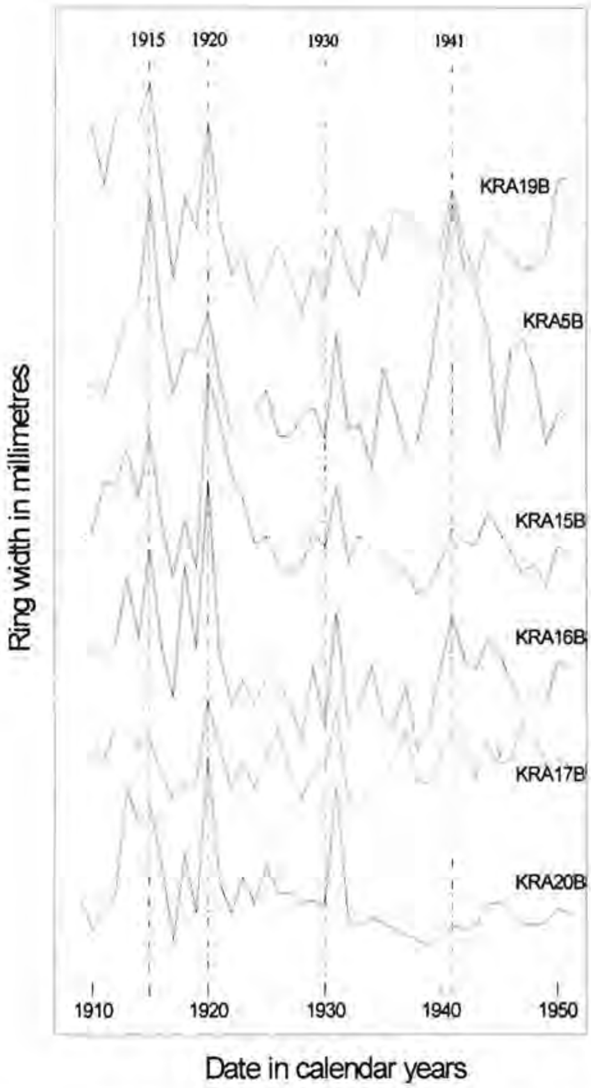

Figure 15. Portions of ring width plots for six trees that form part of the Krakadouw site chronology illustrating cross-dating in the period 1910 - 1950.

Those samples which could not be cross-dated were rejected because of several growth features which make cross-dating in this species extremely difficult. Within the *Podocarpus* species lobate growth and especially wedging out of growth rings make cross-dating an impossible task. These two features are not common in *Widdringtonia*. What is common is a lack of definition of the end of the growing season which can often only be properly ascertained by carefully tracing the circumference of the ring on a cross section (Curtis *et al.* 1978). Cross-dating is further complicated by false rings and resin filled bands of cells which are often more clearly defined than the actual growth ring. Ill defined termination of late wood growth was extremely common among the samples from Algeria, whilst being very rare in those samples from Krakadouw. This meant that it was possible to cross-date all the discs (nine) cut at Krakadouw while at Algeria six discs of a potential 16 did not cross-date because of lack of definition in ring structure.

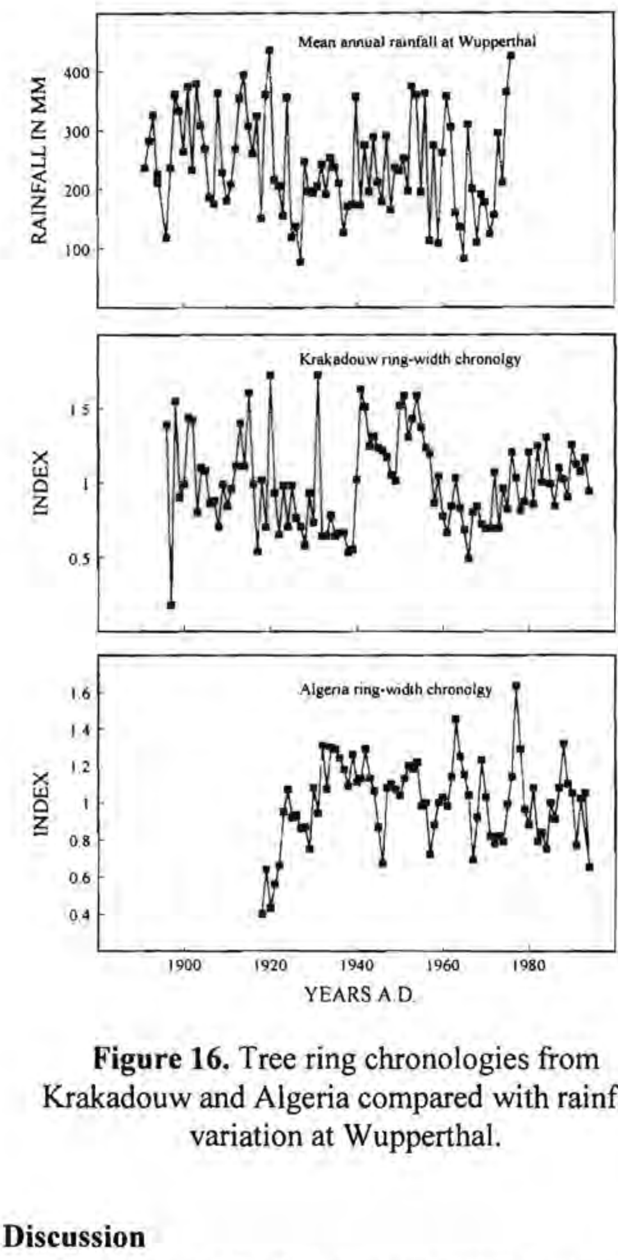

Figure 16. Tree ring chronologies from Krakadouw and Algeria compared with rainfall variation at Wupperthal.

Using the computer programme ARSTAN (International Tree Ring Data Base) a chronology was built using 22 selected ring width series from 11 trees at Krakadouw (Fig. 16) and 25 series of 14 trees from Algeria (Fig. 16). These chronologies were correlated with rainfall figures from Algeria and Wupperthal. The result of the correlation coefficient analysis of average annual rainfall and ring width index chronology for Algeria shows that the trees at this site are less sensitive to rainfall ($R = 0.06$, NS) than those at Krakadouw ($R = 0.48$, $P<0.001$). There is a strong positive correlation between rainfall values from the two sites ($R = 0.75$, $P < 0.001$) with no significant correlation between ring width indices ($P < 0.05$).

Discussion

Unlike the many North American and European trees used for dendrochronology most South African woody species are not suitable for such purposes (Lilly 1977). Differing from the various *Podocarpus* species, circuit uniformity of *Widdringtonia cedarbergensis* is usually good, with lobate growth and wedging out of individual rings being uncommon. There is also a good approximation between age determination through ring counts and actual age of the trees. However, Dunwiddie and La Marche (1980) sampled 46 trees (58 cores and 25 discs) but only 32 trees (52 radii) make up their final chronology. This means that 30% of the trees sampled by them were found to be unsuitable for dendrochronological analysis. In the present study, 48% of the trees sampled at Krakadouw and 46 % of those sampled at Algeria were found to be unsuitable for analysis. The reasons for this is that many rings lack an abrupt termination of late wood growth and many have several false bands within the late wood, making determination of the precise ring boundary difficult. With discs it is often possible to trace the circumference of the ring, however, using cores this is not possible. As a result, only 21 % of the cores and 100% of the discs from Krakadouw and 30% of the cores and 62 % of the discs from Algeria were utilised in the final chronologies. These results indicate that although age determination of *Widdringtonia cedarbergensis* based on ring counts is possible, a high percentage of the wood collected in the field will be unsuitable for dendrochronological purposes. *Widdringtonia cedarbergensis* is an endangered species. Cutting down trees for discs is not a viable option while it is only possible to cross-date a small percentage (20-30%) of all cores. The vegetation in which these trees grow (fynbos) is fire adapted (Le Maitre & Midgley 1992). Trees killed in the regular fires that sweep the mountains can be used to provide the discs necessary for chronology development.

Rainfall in the Cedarberg Mountains is highly variable with mean averages at Algeria (360 mm) being not only more consistent but also as much as three times higher than at Krakadouw (120 mm). The differences in rainfall at these sites are exhibited in the responses of the ring widths of the trees. At Krakadouw there is a much higher correlation between rainfall and ring width indices than at either Die Bos or Algeria. However, this response to rainfall only represents 23 % of the variation in ring width at Krakadouw and 0.004% at Algeria. While these correlations are significant, they are not sufficiently high for reconstruction of the rainfall record back through time (Zucchini & Hiemstra 1983). Even when only those years with the highest and lowest tree ring indices were compared with the rainfall record, the degree of correspondence did not increase (Fig. 16). Using trees from the driest locations at Krakadouw may increase the correlations between rainfall and ring width indices. Such specimens would have to be located on cliff faces or on top of rocky outcrops with very limited means for accessing water.

The results of this Chapter suggest that the growth of *W. cedarbergensis* is not limited by water stress. However, the trees do lay down rings. These rings cross-date between trees from the same location suggesting that they are annual. The allusion to the annual nature of the rings is borne out by the correlation between estimated age of planting and the tree ring estimates. The abrupt termination of growth manifested in the formation of an annual ring, cross-dateable between trees from the same site, should have a cause common to all of the trees at that site. If this common cause is indeed related to available water then it is possible that stable carbon isotope ratios of tree ring cellulose may reflect this relationship. The next Chapter focuses on the stable carbon isotope ratios of *Widdringtonia* tree ring cellulose based on the premise that $^{13}C/^{12}C$ ratios are elevated with stomatal closure during periods of water stress.

CHAPTER SEVEN

A $\delta^{13}C$ CHRONOLOGY FROM TREE RINGS OF *WIDDRINGTONIA CEDARBERGENSIS* DURING THE 20TH CENTURY, CLIMATIC AND ENVIRONMENTAL IMPLICATIONS.

Introduction

Unlike the various *Podocarpus* species *Widdringtonia cedarbergensis* does form a new ring on an annual basis. This ring is readily identifiable, making dendrochronological age determination and cross-dating possible (Chapter Six). Despite this a dendroclimatological analysis using *Widdringtonia cedarbergensis* does not allow for the main aims of the thesis to be met because the relationship between rainfall and tree ring index chronology is not significant.

Widdringtonia cedarbergensis grows in an environment in which rainfall is severely limited during the hot summer months. The 100 year monthly average rainfall for summer (December to February) is 16 mm at Algeria and 5 mm at Krakadouw. Clanwilliam, which is approximately 26 km from Algeria and 15 km from Krakadouw, has a mean maximum temperature of 35°C and minimum of 16°C for the same period. If this low rainfall at the hottest time of the year is the cause of the annual rings in *W. cedarbergensis,* then this can be tested by measuring the ratio between the stable carbon isotopes ^{13}C and ^{12}C. The basis for this approach is that plants are depleted in ^{13}C relative to atmospheric CO_2 and that the level of depletion is dependent on the photosynthetic carbon reduction pathway. In nature there are three photosynthetic pathways, namely C_3, C_4 and CAM.

Plants using the C_3 pathway or Calvin Cycle include all trees, most shrubs as well as temperate grasses and grasses from shaded forests (Calvin & Benson 1948). Most tropical grasses and a few dicotolydenous plants use the C_4 pathway (Hatch & Slack 1966). The CAM (Crassulacean Acid Metabolism) pathway is restricted to succulents (Osmond 1978). The focus of the present study is trees and therefore, by definition, on the C_3 photosynthetic pathway. C_3 photosynthesis involves the conversion of atmospheric CO_2 into the three carbon molecule, phosphoglyceric acid, by the ribulose-1,5-biphosphate carboxylase enzyme (RuBP carboxylase, Zelitch 1979). The carbon thus formed is transported from the leaf to the stem where it is laid down on an annual basis in the rings of the tree. An isotopic examination of these growth rings should therefore represent a record of $^{13}C/^{12}C$ variations in atmospheric CO_2 or of physiological responses to climate or a combination of both (Francey & Farquhar 1982).

Before nuclear weapons testing the ratio of ^{12}C:^{13}C was about 100:1 (Libby 1955). The ratio between these isotopes does change with photosynthesis because ^{12}C is slightly lighter and smaller than ^{13}C and ^{14}C and thus reacts faster (Craig 1953; Park & Epstein 1961; Bender 1968). The physical process of diffusion of CO_2 through stomata and cell membranes, and discrimination against ^{13}C during carbon fixation by the RuBP carboxylase enzyme results in the carbon in plant tissues having relatively more ^{12}C and less ^{13}C and ^{14}C than atmospheric CO_2. This process where ^{13}C is discriminated against is termed fractionation. Farquhar *et al.* (1982) have formulated the theoretical basis for plant fractionation in the following relationship which emphasises the relatively small discrimination associated with diffusion through the cell wall and the potentially large discrimination caused by RuBP carboxylase;

$$\delta^{13}C_{pl.} = \delta^{13}C_{air} - a - (b-a)\, C_i/C_a$$

where $\delta^{13}C_{pl.}$ and $\delta^{13}C_{air}$ are the isotopic ratios of plant and atmosphere(~ -8‰) respectively, a = fractionation associated with stomatal diffusion (~ 4.4), b = fractionation by RuBP carboxylase (~ 30‰), C_i = internal leaf CO_2 concentration and C_a = atmospheric CO_2 concentration. The ratio of ^{13}C to ^{12}C in a sample is compared relative to an internationally-accepted carbonate standard derived from beleminite fossils from the South Carolina Pee Dee Formation (Craig 1953, 1957). This limestone has been arbitrarily assigned a value of 0‰. Because marine carbonates tend to be ^{13}C enriched relative to most natural carbon containing compounds, most substances have negative ^{13}C values (Craig 1957). Carbon $^{13}C/^{12}C$ ratios are calculated relative to this limestone from the equation;

$$\delta^{13}C = \left(\frac{^{13}C/^{12}C_{\text{sample}}}{^{13}C/^{12}C_{\text{standard}}} - 1\right) \quad X1000‰$$

Relative to PDB the $^{13}C/^{12}C$ ratio of a sample is designated as $\delta^{13}C$ and are given as parts per thousand (ppt or ‰). More negative $\delta^{13}C$ values mean less ^{13}C and more positive values more ^{13}C (Craig 1957).

For C_3 plants ^{13}C depletion resulting from photosynthesis results in plant $\delta^{13}C$ values around -27‰ with a range from -20‰ to -35‰. This range in $\delta^{13}C$ values is attributable to a number of environmental factors including ambient $\delta^{13}C$ values for CO_2 (usually around -8.0‰, Keeling *et al.* 1979), light intensity (Ehleringer *et al.* 1986; Gebauer & Schulze 1991; Medina *et al.* 1991), water stress (Freyer & Belacy 1983; Farquhar & Richards 1984; Hubick *et al.* 1986; Ehleringer & Cooper 1988), nutrient status of the soil (Bender & Berge 1979; Hattersley 1982) and temperature (Smith *et al.* 1976).

The main focus of this Chapter is the relationship between carbon isotope values of wood cellulose across the diameter of a tree and the amount of water available to the tree. The basic hypothesis is that stomatal closure during periods of moisture deficiency should lead to elevated $^{13}C/^{12}C$ ratios as a reduction of available CO_2 during this period leads to diminished photosynthetic discrimination against the heavier ^{13}C isotope in favour of the lighter ^{12}C isotope (Francey & Farquhar, 1982). Ehleringer and Cooper (1988) sampled various species along a moisture gradient in California and identified a change in $^{13}C/^{12}C$ ratios from -24.2‰ in the driest habitats to -26.5‰ in wetter conditions. Lipp *et al.* (1994) analysed the late wood of annual rings from spruce trees grown in Middle Franconia, Germany which showed significant correlations with precipitation rates for July and August. This Chapter attempts to utilise this relationship between carbon isotope values of wood cellulose across the diameter of a tree and the amount of water available to the tree in the development of a high resolution rainfall record for the Cedarberg mountains.

Methods

In the southwestern Cape, Dunwiddie and La Marche (1980) report on the development and interpretation of an annual ring width index chronology of the Clanwilliam cedar (*Widdringtonia cedarbergensis*). The Dunwiddie and La Marche (1980) chronology was derived from 52 radii of a total of 32 trees from a site in the Cedarberg mountains (Fig. 14) near Cape Town called Die Bos (32° 24' : 19° 13') at an elevation of 1330 m. The two cores from each of six of these trees with the highest correlations in ring width measures were taken for stable carbon isotope analysis (cores 10b, 10c, 11a, 11b, 42b, 42c, 44b, 46a, 46c, 49a, 49b). The most recent pith age for the 11 cores used in this study is 1881 which allows for a sufficient interval not to have any increase in isotope values which may be attributed to the "juvenile effect" (Francey and Farguhar 1982). The individual rings from 1900 to 1977 were removed from the cores with a scalpel under a stereo microscope (Wild M3C - Switzerland). The annual rings from the six trees were then pooled to form a combined sample for each year to produce a site representative chronology.

Cellulose has become the preferred material for isotope analysis of tree rings because of its chemical stability and composition relative to whole wood which is composed of a number of different components each with a different isotopic composition (Leavitt & Danzer 1993; Sheu & Chiu 1995). Also, the cellulose is relatively immobile remaining confined to the ring in which it is formed as opposed to whole tissue which may contain some mobile compounds from across the ring boundary (Leavitt & Danzer 1993). The method used here to extract holocellulose from wood was the technique of acid, sodium chlorite delignification developed by Leavitt and Danzer (1993) after Green (1963). After milling, the samples with corresponding plastic identity tags were put into pouches made from 6 cm diameter #30 Schleicher and Schuell glass fibre paper. These pouches were closed using 2.5 mm wide nylon cable ties. A set of between 20 - 30 pouches fit into a soxhlet extractor.

Oils, resins and waxes were leached from the sample in the first step, over 17 hours in the soxhlet extractor using a 2:1 (300:150 ml) toluene/ethanol mixture. In the second step the samples were allowed to dry for 1-2 hours in a fume cupboard before being returned to the soxhlet extractor with 100% ethanol. After a further 17 hours the samples were again dried before being boiled in 700 ml of deionised water to remove any water soluble gums, salts and starches. Six hours later the water was decanted from the Erlenmeyer flask which was then topped up with 700 ml of deionised water, 8 grams of sodium chlorite and 1 ml of acetic acid. The flask was left on a hot plate at 70°C with a small 50 ml Erlenmeyer flask inverted over the top to act as a stopper. After 16 hours four more additions of sodium chlorite (7 - 8 g) and acetic acid (1 ml) were made at two hourly intervals. The samples were decanted and irrigated with deionised water overnight before being oven dried. The pouches were finally opened to remove the cellulose by cutting the cable ties with a small wire cutter (after Green 1963; Leavitt & Danzer 1993).

All stable carbon isotope analysis was carried out in the Archaeometry laboratory at the University of Cape Town. The cellulose sample (20 mg), copper oxide and a piece of silver foil were loaded into quartz tubes, the tubes evacuated to less than 10^{-2} Torr, sealed off with an oxy-butane torch and heated for a minimum of four hours at 800° C (Sofer 1980; Sealy 1986). After cooling, the tubes were removed from the furnace, scored in the middle to ensure easy cracking and to prevent splitting and inserted into a cracker of the type described by Desmarais and Hayes (1976). The combustion process produces CO_2, nitrogen and water vapour which are separated from each other on a cryogenic gas separation line into which the tube was inserted (Sealy 1986). The line was then evacuated to 10^{-4} Torr before the sample was cracked. Liquid nitrogen placed over the traps froze the CO_2 and water vapour, allowing the nitrogen to be pumped away. The water vapour was then separated from the CO_2 by placing a dry ice/alcohol slurry over the traps which froze out the water vapour but not the CO_2. The CO_2 yield was measured on a manometer before the gas was frozen into a tube using liquid nitrogen. The tube was then sealed off with the oxy-butane torch before insertion into the cracker on the mass spectrometer

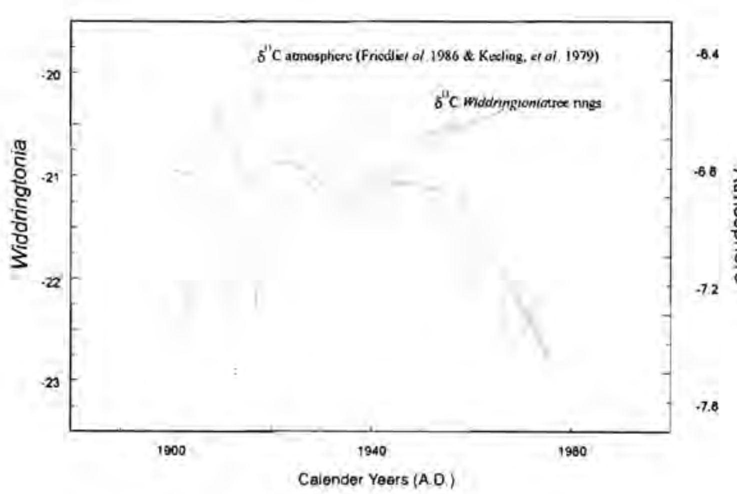

Figure 17. Comparison of the $\delta^{13}C$ trends between *Widdringtonia* (This study) and atmospheric measures (Friedli *et al.* 1986 & Keeling *et al.* 1979, 1980).

Stable carbon isotope measures were carried out on a Micromass 602 E spectrometer. This is a 90° sector double collector instrument with dual inlet system. The references were done against a laboratory gas related to the Chicago PDB marine carbonate standard by calibration against six NBS reference standards (see van der Merwe 1982 & Sealy 1986).

Rainfall data for Wupperthal (32° 16' S:19° 13' E) the closest rainfall station to the Die Bos site was obtained from the Weather Bureau, Dept. of the Environment, Pretoria. Mean precipitation data as well as precipitation data for winter, spring, summer and autumn, plus combinations of these were correlated with $\delta^{13}C$ values.

Table 6. $\delta^{13}C$ values for *W. cedarbergensis*, Wupperthal rainfall and an extrapolation of the $\delta^{13}C$ values of the atmosphere based on direct measures by Keeling *et al.* 1979, 1980 and the Siple ice core results of Friedli *et al.* (1986).

DATE	*Widdringtonia* $\delta^{13}C$, ‰	Rainfall mm	Atmosph. $\delta^{13}C$, ‰	DATE	*Widdringtonia* $\delta^{13}C$, ‰	Rainfall mm	Atmosph. $\delta^{13}C$, ‰
1900	-21.51	329	-6.77	1939	-20.58	170.5	-6.87
1901	-21.53	264	-6.78	1940	-21.22	173.4	-6.85
1902	-21.45	374.1	-6.79	1941	-21.22	389.9	-6.84
1903	-22.53	231.7	-6.80	1942	-21.09	257.3	-6.83
1904	-21.95	378.8	-6.76	1943	-20.77	253.7	-6.82
1905	-22.48	308.6	-6.71	1944	-21.08	195	-6.82
1906	-22.21	268.2	-6.67	1945	-21.73	288.4	-6.83
1907	-22.04	186.5	-6.63	1946	-21.18	210.1	-6.83
1908	-21.43	174.3	-6.58	1947	-20.99	178.5	-6.83
1909	-21.76	363.4	-6.54	1948	-21	290.4	-6.84
1910	-22.35	237.9	-6.59	1949	-21.19	164.9	-6.84
1911	-22.44	180.9	-6.65	1950	-21.29	235.8	-6.84
1912	-21.78	206.9	-6.70	1951	-21.82	229.9	-6.84
1913	-23.05	267.9	-6.75	1952	-21.39	251.2	-6.85
1914	-22.23	354.2	-6.81	1953	-22.1	248.2	-6.85
1915	-21.55	393.4	-6.86	1954	-21.65	386.8	-6.83
1916	-21.34	307.7	-6.84	1955	-21.93	384	-6.81
1917	-22.41	259.2	-6.82	1956	-21.98	194.4	-6.79
1918	-21.39	324	-6.80	1957	-21.59	361.7	-6.83
1919	-21.37	150.7	-6.78	1958	-21.57	113.3	-6.87
1920	-21.71	360.2	-6.76	1959	-21.49	285.4	-6.90
1921	-21.71	435.9	-6.74	1960	-22.32	107.3	-6.94
1922	-21.97	214	-6.75	1961	-21.78	260.8	-6.98
1923	-21.39	204.8	-6.75	1962	-22.2	357.4	-7.02
1924	-21.5	155	-6.76	1963	-21.93	305.1	-7.06
1925	-22.05	355.7	-6.77	1964	-22.18	159	-7.09
1926	-22.16	117.7	-6.77	1965	-22.03	136	-7.13
1927	-21.53	137.3	-6.78	1966	-21.78	82	-7.17
1928	-21.44	76.5	-6.80	1967	-22.72	309.1	-7.20
1929	-21.22	246.1	-6.81	1968	-22.58	200	-7.24
1930	-21.03	195.7	-6.83	1969	-22.47	109.5	-7.27
1931	-21.53	193.5	-6.85	1970	-22.15	190.5	-7.31
1932	-21.08	203.6	-6.86	1971	-22.65	176.5	-7.34
1933	-21.00	240.6	-6.88	1972	-22.38	123.5	-7.38
1934	-21.37	190.7	-6.89	1973	-22.36	155.9	-7.41
1935	-21.39	252.3	-6.91	1974	-22.81	294.3	-7.45
1936	-21.92	236.6	-6.90	1975	-22.79	209.5	-7.48
1937	-21.54	200.7	-6.89	1976	-23.08	363.5	-7.52
1938	-21.85	126.2	-6.88	1977	-23.22	230.8	-7.55

Results

The original $\delta^{13}C$ values of the cellulose from the annual tree rings of the six trees from the Die Bos site are given in Table 6. These values are plotted as a chronology in Fig. 17. The most notable aspect of the curve is the long term trend toward progressively less negative values to 1939 (more ^{13}C) after which values plateau out to 1947 when they rapidly become more negative (less ^{13}C) to 1977 (Fig. 17). Mean $\delta^{13}C$ values for the five years 1900 to 1904 are -21.79‰ which is only 0.58‰ ($P<0.05$, t test) different from the 1945 to 1949 (-21.22‰) pentad. The difference between the 1945 - 1949 pentad and that of 1973 - 1977 (-22.85) is 1.64‰ ($P< 0.0001$, t test). Correlations with various combinations of monthly and annual rainfall are not significant ($P > 0.05$) even when the original data set is de-trended for the anthropogenic CO_2 contribution using the data obtained by Friedli *et al.* (1986) from ice cores and the direct atmospheric measures of Keeling *et al.* (1979 and 1980, Fig. 18).

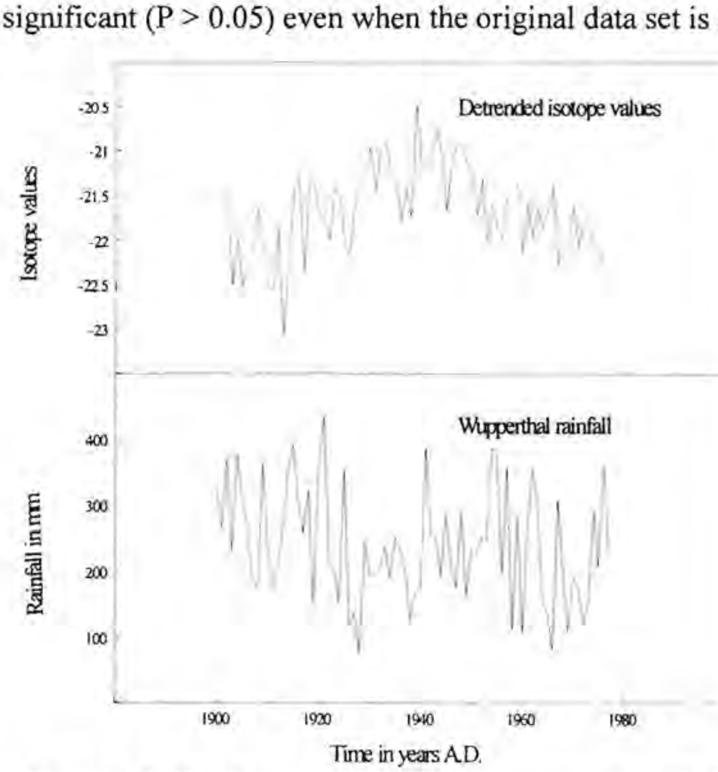

Figure 18. Relationship between mean annual rainfall and de-trended $\delta^{13}C$ values for *W. Cedarbergensis*.

The *Widdringtonia* isotope chronology does, however, show significant correlations with a $\delta^{13}C$ atmosphere chronology computed from the data obtained by Keeling *et al.* (1979 and 1980) and Friedli *et al.* (1986) ($r = 0.51$, $P < 0.0001$, Fig. 17) and with the results obtained from maize (*Zea mays*) kernel cellulose by Marino and McElroy (1991, $r = 0.66$, $P < 0.0001$, Fig. 19).

Discussion

The primary objective of this Chapter is an assessment of the feasibility for using stable carbon isotope measures of the cellulose extracted from tree rings as an alternative to ring width measures to provide a rainfall index through time. As with the relationship between ring width measures and precipitation (Chapter Six) $\delta^{13}C$ values do not correlate well with various combinations of monthly and annual rainfall ($P > 0.05$, Fig. 18). Fritts (1976) and others (Norton *et al.* 1989; Cook *et al.* 1992) have shown that the general response of trees is to produce narrow rings in warm dry years and wide ones in cool wet years, while Francey and Farquhar (1982) have demonstrated that extreme water stress can cause stomatal closure which reduces CO_2 uptake resulting in more positive $\delta^{13}C$ values. At the Die Bos site, high summer temperatures are combined with dry conditions (mean rainfall values for Wupperthal are 5.33 mm in summer) which should lead to less negative $\delta^{13}C$ values. Contrary to these expectations the results for the present study indicate no significant correlations between $\delta^{13}C$ values of cellulose and the various combinations of rainfall data ($P > 0.05$).

Widdringtonia cedarbergensis tends to grow on rocky islands and ridges protected from the periodic fires that sweep through the Cedarberg Mountains (Le Maitre & Midgley 1992). The location of these trees in the landscape is a textbook example of site selection in dendrochronology as the trees should be sufficiently water stressed to produce annual rings which can be directly associated with rainfall (Fritts 1976; Ferguson 1970). Despite this geographic location and the distinct seasonal nature of the rainfall (see Chapter Two) significant correlations between ring width index chronology and rainfall for either of the two sites are not sufficiently high to allow reconstruction of rainfall through time (Chapter Six). Dunwiddie and La Marche (1980) also did not find significant correlations with rainfall for the Die Bos site nor did Zucchini and Hiemstra (1983) in their re-

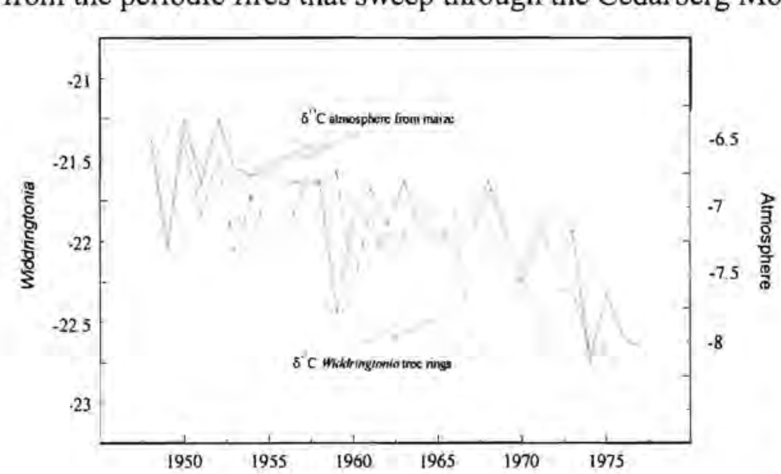

Figure 19. Comparison of the $\delta^{13}C$ trends from *Widdringtonia* (this study) and maize kernels (Marino & McElroy 1991).

evaluation of the Die Bos chronology. These results (see both this chapter and Chapter Six) suggest that contrary to expectations water is not the major limitation to growth for *Widdringtonia cedarbergensis*. Low rainfall at the hottest time of the year is therefore not the cause of the formation of annual rings in *W. cedarbergensis*.

In the fynbos one drought tolerant group of plants can be recognised (Restionaceae), while the limited stomatal distribution of the Ericaceae suggests that this genus uses water conservatively (Stock *et al.* 1992). Like the *Protea* plants cultivated by Richards *et al.* (1995), *W. cedarbergensis* does not fall into either category. With germination in winter, seedlings of *W. cedarbergensis* probably develop root systems capable of maintaining plant water during the hot dry summer months (Stock *et al.* 1992). As the tree matures, it maintains this association with available water so that water stress is never a major limitation to the growth of *Widdringtonia* species. As a result, water stress is not reflected in either tree ring width measures (Chapter Six) nor in $\delta^{13}C$ values of tree rings (this chapter).

Tree rings are complex interactive rather than passive monitors of climate and environment (Leavitt & Lara 1994). The C_i/C_a term as expressed in the fractionation equation of Farquhar *et al.* (1982) is governed by stomatal conductance and the chemical reactions associated with CO_2 assimilation. This relationship means that $\delta^{13}C_{plant}$ can be influenced by physiological responses to the environment. However, a number of authors have noted that $\delta^{13}C$ values of tree rings do not simply reflect environmental $\delta^{13}C$ values but may also be affected by atmospheric CO_2 $\delta^{13}C$ which can be reflected within the tree to show a decline in $\delta^{13}C$ values of approximately 1 - 2‰ from the beginning of the Industrial Revolution (Freyer 1981; Freyer & Belacy 1983; Leavitt & Long 1988; February & van der Merwe 1992; Leavitt & Lara 1994). This depletion in ^{13}C reflected in tree rings over the last ±100 years has been variously attributed to fossil fuel burning and biospheric activities largely related to land use and vegetation cover change (Francey & Farquhar 1982). Trees collect their carbon from free atmospheric CO_2. In rural areas such as the Cedarberg Mountains the value of this CO_2 is at present about -8‰ (Schleser 1994). The value of the pre-industrial atmosphere was around -6‰ (Wigley 1982). Increasing use of fossil fuels which have a $\delta^{13}C$ value around -25‰ has therefore shifted the atmospheric $\delta^{13}C$ signature to more negative values.

The 100-year *Widdringtonia* $\delta^{13}C$ record does show a strong correlation between stable carbon isotope ratios of tree rings and atmospheric carbon dioxide. This correlation is manifested by less negative $\delta^{13}C$ values from 1900 to 1939 after which there is a clear decrease to 1977 which is very similar to that derived from ice core data (Friedli *et al.* 1986, $r = 0.51$, $P < 0.001$, Fig. 17), maize kernel cellulose (Marino & McElroy 1991, $r = 0.66$, $P < 0.0001$, Fig. 19), tree ring $\delta^{13}C$ chronologies from the Northern Hemisphere (Freyer & Belacy 1983) and recent Southern Hemisphere records (Leavitt & Lara 1994).

Previous research for the Southern Hemisphere variously shows no decline in $\delta^{13}C$ values over the last 100 years in Tasmanian tree rings (Francey 1981) or a decline half that for the Northern Hemisphere (Epstein & Krishnamurthy 1990). The first major chronology from the Southern Hemisphere to show any correlation between tree ring $\delta^{13}C$ values and atmospheric CO_2 was a composite 290 year chronology developed for *Fitzroya cupressoides* from a site in Chile (Leavitt & Lara 1994). The present study is only the second chronology, and the first with annual resolution, to show a decline in $\delta^{13}C$ values for trees from the Southern Hemisphere which can be related to the anthropogenic impact on atmospheric CO_2. This curve is very similar to that obtained from European and North American trees which show a decrease in $\delta^{13}C$ values of almost 2‰ from 1850 to 1975 (Francey & Farquhar 1982).

The primary objective of this thesis is, however, not to show relationships between tree ring isotope chronologies and atmospheric CO_2 content but rather to show the relationship between isotopes and rainfall. In this regard this section of the study has not been successful, thereby necessitating the next section of the thesis which experimentally examines the relationship between $\delta^{13}C$ values of wood cellulose and the amount of water available to the tree.

CHAPTER EIGHT

WATER CONSUMPTION AND STABLE CARBON ISOTOPE RATIOS IN *EUCALYPTUS GRANDIS* AND THE HYBRID *EUCALYPTUS GRANDIS* X *NITENS*

Introduction

In the previous chapter a $\delta^{13}C$ chronology for *Widdringtonia cedarbergensis* did not correlate with the rainfall from a nearby weather station. Instead, the trend in the $\delta^{13}C$ chronology can be associated with the anthropogenic CO_2 contribution to atmospheric $\delta^{13}C$ values (Fig. 17 & Fig. 19). Rather than trace the anthropogenic contribution to atmospheric CO_2 the principal goal of this thesis is to provide a high resolution rainfall index extending back in time for more than 100 years. Such long records have only been established for *Abies alba* and *Picea abies* (Lipp *et al.* 1991, 1994). However, a number of researchers have shown that plant $\delta^{13}C$ ratios not only reflect atmospheric CO_2 levels but are also good indicators of water available to plants (Freyer & Belacy 1983; Spittlehouse 1985; Carter & Klinka 1990; Dupouey *et al.* 1993; Leavitt & Long 1989 & 1994). The results obtained for *W. cedarbergensis* (Chapter Seven) are therefore contrary to the results obtained from previous research. These contradictory results defined a need to experimentally determine the relationship between $\delta^{13}C$ values of wood cellulose and plant available water. To develop a better understanding of changes in wood cellulose $\delta^{13}C$ values and plant available water in natural ecosystems detailed measurements of plant water demand, soil structure and climate are required. To meet these requirements most studies have utilised computer models to determine soil water storage and transpiration rates (Dupouey *et al.* 1993; McNulty & Swank 1995; Livingston & Spittlehouse 1993, 1996). Rather than resort to complex measures or computer modelling the plants used in this chapter were grown under controlled watering treatments. This would allow for directly correlations to be made between $\delta^{13}C$ values of wood cellulose and the amount of water used by the plant in a specific watering treatment. The determination of this link in real terms should lead to a better understanding of the relationship between tree ring $\delta^{13}C$ values, plant available water and plant water use.

Methods

The trees used in this experiment were originally grown for an experiment designed to select for drought tolerant and productive *Eucalyptus* spp. at the D.R. de Wet Forestry Research Station (FORESTEK) by Le Roux (1993; Le Roux *et al.* 1996, Fig. 20). The methods used were described by her, and the following paragraph makes extensive use of that description (Le Roux 1993; Le Roux *et al.* 1996; February *et al.* 1995). On 21 March 1991 ten week old cuttings of *E. grandis* and the hybrid *E. grandis* x *nitens* were planted at 15 cm below soil surface in 220 litre drums, in the field, at the D.R. de Wet Forestry Research Station (25° 3' 10": 30° 53' 30"). 3:2:1 NPK fertiliser (100g) and 2 litres of water were added to each drum at the time of planting. Rainfall was excluded from the drums by specifically adapted plastic sheets which allowed for the protrusion of the leaf stem and canopy. The drums were sunk in the soil with only the top 60 cm protruding to simulate, as closely as possible, actual growing conditions. Half of the individuals were subjected to a low watering treatment and the remainder to a high treatment where soil moisture in the drum was maintained at 60 and 80 litres respectively. Soil moisture depletion through root uptake was measured each week with a neutron probe and the required amount of water used per plant was calculated over the 16 month growth period from when the cuttings were planted to when the plants were harvested (Le Roux 1993; Le Roux *et al.* 1996).

Figure 20. Map showing location of D.R. de Wet Research Station * in Mpumalanga.

Previous research has indicated that $\delta^{13}C$ values of whole leaf tissue and leaf cellulose become more negative with increasing distance from the base of the tree depending on canopy position, i.e. aspect and height (Le Roux 1993; Le Roux *et al.* 1996). In contrast to the behaviour of the leaves, however, the corresponding cellulose of the trunk does not show any significant $\delta^{13}C$ gradient (Schleser 1992). The reason for this is that the trunk carbon is composed of carbon fixed by all the leaves during photosynthesis (Schleser 1994). Despite these assurances and as a control for possible variation only the main stem wood between ± 50 mm and ± 110 mm above the soil was analysed in the present study. A further control for possible variation in $\delta^{13}C$ values across the diameter of the stem was made by analysing a standard section of the secondary xylem 1 - 2 mm in towards the pith from the cambium. This standard section means that the wood analysed from each tree contains the same year.

Stem diameters, excluding the bark were measured at the widest point using dial callipers after which the transverse sectional area of the stem was measured and calculated using a binocular microscope (Wild - Switzerland) and the image analysing programme FIPS from the CSIR (Council for Scientific and Industrial Research) Pretoria. After measurement, the wood was prepared for stable carbon isotope analysis as described in Chapter Seven.

Results

For both taxa water availability had a significant effect on mean total water consumed ($P < 0.001$) which in turn had a significant influence on stem diameter ($P < 0.0001$) and transverse sectional stem area ($P < 0.0001$; Table 7). $\delta^{13}C$ values of wood cellulose are significantly correlated with both water treatment (Table 7) and water consumed (Figs. 21 & 22). Stable carbon isotope ratios for *E. grandis* are, however, more negative (-25.65‰, -26.19‰) than

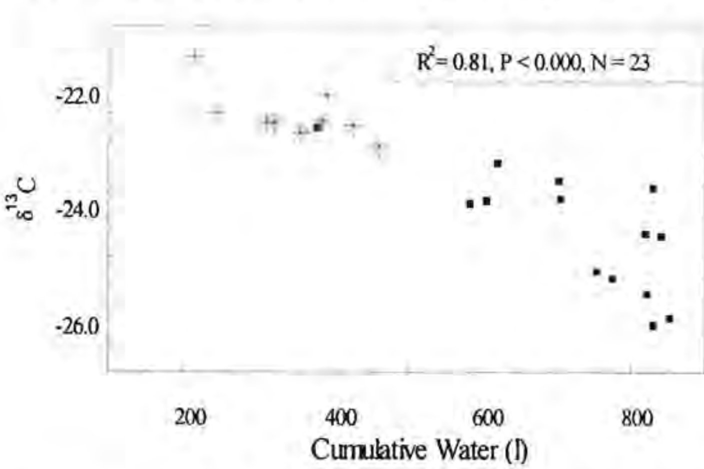

Figure 21. Relationship between $\delta^{13}C$ values and water consumption for *Eucalyptus grandis* in wet ▪ and dry treatments

those for*E. grandis* x *nitens* (-23.96, -24.37).These differences in isotope values correspond with a much higher water consumption for *E. grandis* (max. 850 *l*, Fig. 21) than for *E. grandis* x *nitens* (max. 827 *l*, Fig. 22). Intraclonal variance in $\delta^{13}C$ values for *E. grandis* is between -21.51‰ (216 *l* of water) and -26.19‰ (829 *l* of water). For *E. grandis* x *nitens* intraclonal variance was much smaller, between - 21.47‰ (199 *l*) and -24.29 (827 *l*). In both the wet and dry treatments *E. grandis* consumed more water than *E. grandis* x *nitens* (Figs 21 & 22 and Table 7).

Discussion

Plants with the C_3 photosynthetic carbon reduction pathway have stable carbon isotope ratios about -19.00‰ lower than that of the atmosphere (Francey & Farquhar 1982). Within the C_3 grouping ^{13}C depletion resulting from photosynthesis results in plant $\delta^{13}C$ values around -27‰ with a range from -20‰ to -30‰. This range in $\delta^{13}C$ values is attributable to a number of environmental factors including ambient $\delta^{13}C$ values for atmospheric CO_2 (usually around -8‰, Keeling *et al.* 1979, 1980; Freyer 1981; Leavitt & Long 1988; Leavitt & Lara 1994) and water stress (Freyer & Belacy 1983; Farquhar & Richards 1984; Hubick *et al.* 1986; Ehleringer & Cooper 1988; Schleser 1994). Within the experiment outlined in this chapter all plants were exposed to the same degrees of light intensity, atmospheric CO_2 levels, soil nutrients and ambient temperature (environmental variables); only available water varied.

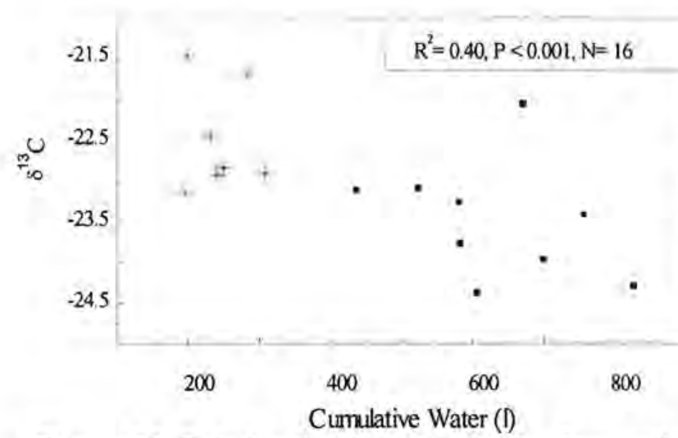

Figure 22. Relationship between $\delta^{13}C$ values and water consumption for *Eucalyptus grandis* x *nitens* in wet ▪ and dry + treatments

The results indicate that for both species of *Eucalyptus* carbon isotope ratios are significantly correlated with both water treatment and water consumption (Figs 21 & 22 and Table 7). The slope of the two graphs does change depending on the species but the trends are the same indicating that C_i values increase with increasing soil water availability and with increasing water consumption resulting in more negative tree ring cellulose $\delta^{13}C$ values (Figs 21 & 22 and Francey & Farquhar 1982). The fractionation associated with the translocation of carbon from the leaves to the stem and its conversion to cellulose and lignin is assumed to be negligible by Francey & Farquhar (1982) while Leavitt and Long (1982) have indicated that there is an additional fractionation effect from the leaves to the wood of +2‰. The possible discrimination between tree ring and leaf cellulose is constant and should not affect studies concentrating on tree rings but should be taken into account when comparing results between tree ring and leaf cellulose.

Table 7. The differences between plant growth and $\delta^{13}C$ values of *E. grandis* and *E. grandis* x *nitens* after cultivation under different watering treatments. Values are means for the number of plants indicated. NS denotes no significant difference between means and *, **, ***, **** indicate significant difference between means at $P < 0.05$, 0.01, 0.001 and 0.0001 respectively.

	Variable	*Watering treatment*				
		Dry	***Std Dev***	***Wet***	***Std Dev***	***t test***
grandis						
	Nº of plants	11		14		
	Stem diameter (mm)	21	1	26	2	****
	Stem area (cm^2)	3.4	0.35	5.3	0.72	****
	Water uptake (*l*)	349	75	723	130	****
	Nº of plants	9		14		
	δ13C, ‰	-22.5	0.45	-24.5	1.03	****
grandis* x *nitens						
	Nº of plants	8		9		
	Stem diameter (mm)	19	2	27	3	****
	Stem area (cm^2)	2.9	0.6	5.5	1	****
	Water uptake (*l*)	252	41	631	113	****
	Nº of plants	7		9		
	δ13C, ‰	-22.5	0.65	-23.5	0.72	**

The range in $\delta^{13}C$ values within a specific treatment (Table 7) does indicate that there is a large range in isotope values possible within a species. This does propose that different individuals of the same species from the same location may not produce similar isotope signals when exposed to the same environmental conditions. The implication is that any genetic differences which relate to stomatal conductance or CO_2 transfer can and do affect the $\delta^{13}C$ values of the individual (Leavitt & Long 1984;

1986b). This would mean that all the trees from a particular location may have the same genetic makeup but would not necessarily have the same $\delta^{13}C$ values. Previous research has shown an intrasite variability in $\delta^{13}C$ values of 2 to 3‰ (Leavitt & Long 1984; 1986a). These results are in complete agreement with the present study that shows similar figures for the different treatments although values are somewhat higher for *E. grandis* (~4‰). The implications are considerable in that the wood sampled from one tree cannot be said to be representative of the site from which it was collected. The emphasis in tree ring isotope research should therefore be on pooling four or more trees from one site (Leavitt & Long 1984; 1986b). This practice does not average widely divergent trends in $\delta^{13}C$ values but it does provide a composite time series which can be representative of the whole site (Leavitt & Long 1986b). The differences in isotopic values between the two species utilised in this experiment indicates that interspecies variability in $\delta^{13}C$ values should also be recognised and accounted for when conducting isotope research on different species from different locations.

These results suggest that the $\delta^{13}C$ values of tree wood cellulose may be useful in rainfall reconstructions, provided that the trees chosen for analysis are sensitive to changes in rainfall, that atmospheric isotope correlations are understood, and that all environmental constraints are taken into consideration.

CHAPTER NINE

STABLE CARBON ISOTOPE RATIOS IN CHARCOAL AND WOOD CELLULOSE OF *COMBRETUM APICULATUM* AND *PROTEA ROUPELLIAE* AND RELATIONSHIPS WITH RAINFALL

Introduction

Based on an analysis of the charcoal recovered from archaeological sites a number of researchers have provided information on climate and environment change through time (Chapter Three, Prior & Price Williams 1985; Tusenius 1989, February 1992b). In all of these studies, however, the emphasis lay in a detailed analysis of environmental change based on wood identification from xylem anatomical structure. Moving away from this traditional approach, this chapter examines the potential for using $^{13}C/^{12}C$ ratios of *Combretum apiculatum* and *Protea roupelliae* charcoal from archaeological sites as a climate indicator. The Chapter is based in previous research which indicates that the isotopic composition of carbon stored in the growth rings of trees is representative of both $^{13}C/^{12}C$ variations in atmospheric CO_2 as well as physiological responses to environmental change (Chapters Seven & Eight, Freyer & Belacy 1983; Leavitt & Long 1989 & 1994; Farquhar & Richards 1984; Hubick *et al.* 1986; Lipp *et al.* 1994; McNulty & Swank 1995).

Research using *Eucalyptus* spp. has indicated that for *Eucalyptus grandis* and the hybrid *Eucalyptus grandis* x *nitens* $^{13}C/^{12}C$ values are indeed significantly related to the amount of water available to the trees (Chapter Eight). In the principle investigation reported in this chapter samples of both *Combretum apiculatum* and *Protea roupelliae* are examined along a rainfall gradient to ascertain the relationship between $\delta^{13}C$ values and rainfall for these species. An important aspect of the proposed research is to determine and thus exclude any fractionation of the carbon isotope during pyrolysis. To this end, comparisons are made between wood and charcoal to ascertain whether pyrolysis causes any fractionation or merely freezes the isotopic ratios inherent in the wood.

Methods

Protea roupelliae is the most common woody species identified in the archaeological record at Mhlwazini Cave and Collingham Shelter (Chapter Three, Fig. 23), while previous research has indicated *Combretum apiculatum* to be the most common woody species in the archaeological charcoal sample from Dzata in the Soutpansberg Mountains (Fig. 23, February 1992a). The same *P. roupelliae* sample utilised in Chapter Four to determine the relationship between wood anatomical variables and rainfall was also used here. Samples of *C. apiculatum* were collected along a rainfall gradient. Sample collection and preparation for charring is described in Chapter Three.

Figure 23. Map showing location of archaeological sites and location from which an extant sample of *P. roupelliae* and *C. apiculatum* were collected.

To ascertain the relationship between rainfall and $\delta^{13}C$ values in charred wood along a climate gradient some of the freshwood samples were charred as described in Chapter Three. In the laboratory a 2 - 3 cm thick disc was cut of each piece of wood before being wrapped in aluminium foil. These parcels were then placed in a muffle furnace at 400°C for one hour after which the furnace was switched off and allowed to cool overnight. Without further preparation both whole fresh wood and charred samples were analysed for $^{13}C/^{12}C$ ratios as described in Chapter Seven. As in Chapter Eight, a standard section of the secondary xylem 1 - 2 mm in toward the pith from the cambium was analysed. Wood cellulose was prepared by milling, soxhlet extraction and cellulose isolation by delignification (Green 1963; Leavitt & Danzer 1993 and Chapter Seven). All stable carbon isotope analysis was done in the Archaeometry laboratory at the University of Cape Town and stable carbon isotope measures were done on a Finnigan Mat 252 Micromass spectrometer.

References were done against a laboratory gas related to the Chicago PDB marine limestone standard by calibration against six NBS reference standards (see van der Merwe 1982; Sealy 1986 and Chapter Seven).

Results

The results are not consistent for the two species. For *Combretum apiculatum* there is a significant correlation between $\delta^{13}C$ values of the whole wood sample and rainfall (Fig. 24). This relationship is also true of the cellulose extract. After charring at 400°C, however, the $\delta^{13}C$ values of the same wood sample are no longer significantly related to rainfall (Fig. 24).

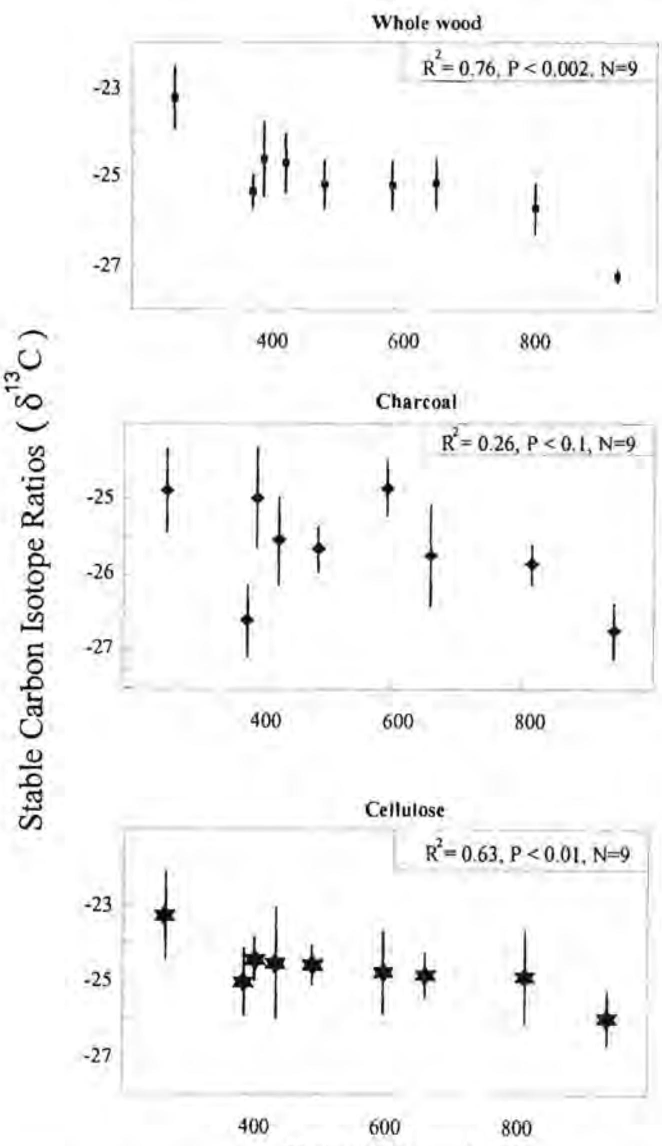

Figure 24. $\delta^{13}C$ ratios for whole wood, wood charred at 400°C, and the cellulose extract of *Combretum apiculatum* along a rainfall gradient in the summer rainfall region of South Africa.

Mean $\delta^{13}C$ values for cellulose are -24.16‰ with a standard deviation of 1‰. Averages for whole wood are more negative by 1‰ at -25.2‰ (std. dev. 1‰) while wood charred at 400°C is again more negative by 0.5‰.

Previous research has indicated that there is a significant correlation between xylem vessel size and frequency of *P. roupelliae* and rainfall (Chapter Four). The result of a stable carbon isotope analysis of a charred fraction of this same sample shows no significant correlation between $\delta^{13}C$ values and rainfall (Fig. 25). The cellulose extract of a smaller sample was re-analysed to check this finding. Again, there is no significant correlation between $\delta^{13}C$ values and rainfall (Fig. 25). Mean $\delta^{13}C$ values for cellulose are -24.76‰ whereas the charcoal sample has a mean $\delta^{13}C$ value of -25.88‰. This represents a fractionation effect of ~1‰ from cellulose to charcoal.

Discussion

Previous research has indicated that there is a strong correlation between $\delta^{13}C$ values and available water (Chapter Eight). The results of a $\delta^{13}C$ analysis of both whole wood and cellulose in this chapter does show that rainfall is indeed significantly related to $\delta^{13}C$ values of *C. apiculatum,* however, there is no significant correlation for *P. roupelliae*. These results confirm the conclusion of others (Stock *et al.* 1992; Richards *et al.* 1995) that suggests that water stress is never a major limitation to the growth of *Protea* species. Within the neighbouring Fynbos Biome, described as having a summer moisture deficit, various researchers working with *Protea* have not been able to detect plant moisture stress as indicated by xylem pressure potentials (Miller *et al.* 1983; Van der Heyden & Lewis 1988). The reason for relatively high xylem pressure potentials in *Protea* species has been attributed by Van der Heyden and Lewis (1988) and Manders and Smith (1992) to the rapid development and maintenance of root systems allowing access to deep soil moisture. Therefore, as with *Widdringtonia cedarbergensis* (Chapter Seven) water

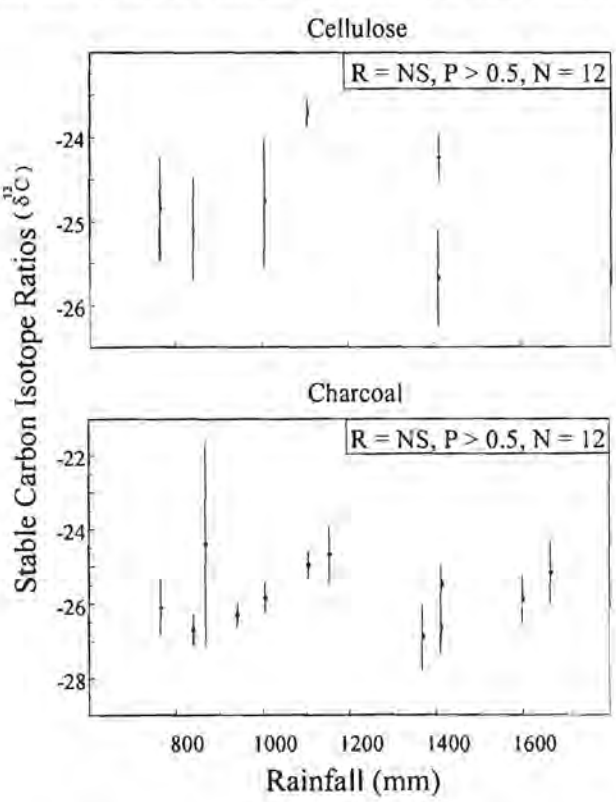

Figure 25. $\delta^{13}C$ ratios for wood charred at 400° C and the cellulose extract of *Protea roupelliae* along a rainfall gradient in the summer rainfall

stress is never a major limitation to the growth of *Protea* species in the Fynbos Biome (Stock *et al.* 1992; Richards *et al.* 1995). The relationship between vessel diameters and rainfall for *P. roupelliae* (Chapter Four) does, however, contradict the isotope results of this chapter. Some of this difference in results for the two species can probably be attributed to *C. apiculatum* being drought deciduous, with very definite seasonality of growth related to rainfall. *Protea roupelliae,* on the other hand, does not lose its leaves. Rather, these leaves may stay on the plant for a number of years (pers obs). This tendency could affect the isotope ratios in that $\delta^{13}C$ values of previous years are retained in the leaf and may be distributed to the rest of the plant in subsequent years.

More likely, these contradictory results are attributable to habitat. *P. roupelliae* grows in a wide variety of habitats and on a range of soil types and depths as well as in areas of very high rainfall whereas the *C. apiculatum* sample comes from a much smaller area. The *Protea* sample analysed here was collected over a distance of more than 1000 km from Umtamvuna on the Kwazulu - Natal south coast to Serala (Wolkberg) in the Northern Province (Fig. 23), from sea level to an altitude of more than 2000 metres. This would suggest that a range of ecophysiological factors and environmental variables probably accounts for the variations in $\delta^{13}C$ values among *P. roupelliae* trees from different locations found in this study. As the objectives of the thesis are to develop long rainfall chronologies these apparent contradictory results should be the focus for future research. For the present, the non significant results obtained here suggest that *Protea roupelliae* charcoal recovered from archaeological sites cannot be used in climate reconstructions based on stable carbon isotope evaluations.

The highly significant correlations of $\delta^{13}C$ values and rainfall for *C. apiculatum* are, however, not manifested in the sample charred at 400° C. Prior and Gasson (1993) demonstrate that at 400°C the percentage weight loss of *Combretum zeyheri* was approximately 47%. The cell walls of wood are composed of a characteristic mixture of polymers of cellulose, carbohydrates and lignin (Panshin and de Zeeuw 1980). Prior and Gasson (1993) suggest that during pyrolysis hemicelluloses degrade at temperatures between 200 and 300°C followed by cellulose above 240°C and lignin above 280°C. Thus the main components of wood are degraded at temperatures under 300°C. On average this degradation is represented in $\delta^{13}C$ values becoming more negative by 0.5 ‰ at temperatures of 400°C and by 1‰ at temperatures of 500°C.

However, this fractionation is not a constant with different pieces of wood reacting differently depending on a number of factors including size and location to the heat source. As a result, the significant correlations obtained for both whole wood and the cellulose extract of *Combretum apiculatum* is not maintained when wood is charred. This would suggest that the charcoal recovered from archaeological sites cannot be used in $\delta^{13}C$ reconstructions of rainfall.

CHAPTER TEN

SYNTHESIS

While temperature data are relevant to climate studies, the major socio-economic concern in South Africa is the impact of rainfall unreliability. This has never been more evident than during the 1991/1992 drought in which millions of tons of maize were lost and many thousands of people were faced with starvation. It is droughts such as these that has thrown into focus the need for both better management of the present water resources and the forward planning for the enhancement of the water supply. Such a focus requires a projection on the range of climates which can be expected in the future. An examination of the past to predict future climates has recently gained universal acceptance with the establishment of the International Biosphere Geosphere Programme (IGBP) in the mid 1980's. However, without long term accurate rainfall chronologies, predictions based on computer models are questionable since the outputs from these models are only as good as the data that have gone into them. It is therefore fundamentally important to South African agriculture that long rainfall records are established. This thesis addresses the need for a high resolution proxy rainfall data set that goes beyond the historic record.

At present there are no methods utilised in South African palaeoecology are able to produce high resolution rainfall data sets. With this objective as a goal, the thesis evaluates four techniques which are not commonly utilised by South African palaeoecologists. The primary objective is the development of one high resolution (annual or decadal scale in mm) method for reconstructing rainfall with at least two other techniques which may not have the resolution but can be used to evaluate the results. The first two techniques evaluated fall into this latter category in that the resolution of the time series is governed by radiocarbon dates (Chapters Three & Four). While radiocarbon dating is reliable, it cannot be used to accurately define archaeological stratigraphic units in single years or even decades but rather to place a set of assemblages within a specific age group (Atwater, Stuiver & Yamaguchi 1991). Notwithstanding this drawback, the results obtained from both taxonomic identification (Chapter Three) and xylem analysis (Chapter Four) suggest that such an evaluation of archaeological charcoal samples may be useful for reconstructing environments and rainfall patterns through time. The dating of the other two techniques evaluated (Chapters Five-Six and Seven-Nine) has a much higher resolution as it is based on the assignment of each successive growth ring within a tree to the year in which it was formed. Despite this resolution, however, it was not possible to reconstruct rainfall patterns through time using either dendrochronology (Chapters Five-Six) or stable carbon isotope analysis of wood cellulose and charcoal (Chapters Seven-Nine).

Research focusing on the taxonomic identification of charcoal from archaeological sites, relies upon a knowledge of the ecological requirements of extant species to develop hypotheses on the climate and environment at the time the charcoal was formed (Salisbury & Jane 1940; Slavikova-Vesela 1950; Vernet 1973; Deacon *et al.* 1983; Prior 1983; Prior & Price Williams 1985; Dowson 1988; Tusenius 1989; Frey *et al.* 1991; Wadley *et al.* 1992; February 1992b; Vernet & Figueiral 1993; Figueiral 1993). Only three of these studies (Vernet 1973; Vernet & Figueiral 1993; Figueiral 1993) has critically evaluated the results in terms of the anthropogenic impact on the environment. None of these studies recognise that the presence or absence of specific indicator species cannot be relied on for useful rainfall reconstructions because of the wide range of climates under which most woody species are able to grow. Many of the woody species that comprise afromontane forests are also evident in the predominant vegetation type (strandveld) along the arid west coast of South Africa. *Podocarpus* spp. for example, grow in both high rainfall afromontane forests such as at Newlands in Cape Town and at Knysna on the south coast with rainfall around 1900 mm as well as at Elands Bay on the west coast at 150 mm. This range would have encompassed any climate change fluctuations which may have occurred over the last 2000 years. The focus has also been on what the environment was like when people were living there rather than what people have done to the environment. Only Vernet (1973), Vernet & Figueiral (1993) and Figueiral (1993) working in Portugal and along the Mediterranean coast of France, acknowledged the potential for human disturbance on the environment. This focus makes the charcoal analytical studies discussed in Chapter Three unique for South Africa in that the anthropogenic rather than climatic influence on the charcoal assemblage is emphasised. These results indicate that rather than climate change it is people that have had the greatest impact on the environment in the vicinity of the archaeological sites of Mhlwazini Cave and Collingham Shelter in the Drakensberg Mountains. This impact has taken the form of too frequent fires which present evidence indicates began at least 400 years ago when agriculturists first moved into the area.

One method does use this charcoal to reconstruct rainfall patterns through time. Scholtz (1986) first realised the potential for using the variation in anatomy of wood charcoal from archaeological sites to infer palaeoclimatic change. Scholtz (1986) proposed a computer based technique for measuring a wide range of potentially ecoclimatically significant variables observable in a cross section of an archaeological charcoal sample (wood anatomical variables related to climate). The present study was a systematic application of Scholtz's (1986) approach to palaeoclimatic reconstruction in order to test its applicability and precision. In this respect it is the first analysis to show that the measurement of specific wood anatomical variables from an archaeological charcoal assemblage may be used to reconstruct rainfall patterns through time (Chapter Four). The results of these measures (xylem analysis) from Collingham Shelter and Mhlwazini Cave reinforce and expand on the little evidence there is for rainfall change in South Africa.

These results also show the first quantified evidence in South Africa for rainfall change during the Little Ice Age (1300 to 1800 A.D.). Much of the previous evidence for a drier cooler Little Ice Age in South Africa has been derived from a reinterpretation of the few tree ring records available (Tyson 1986 and Tyson & Lindsay 1992). The present study, however, contradicts what little evidence there is suggesting that the period prior to 1850 was relatively dry (Tyson 1986 and Tyson & Lindsay 1992). Rather, the implication is that there is a general decrease in rainfall from 2300 B.P. to the present with a slightly wetter period during the Little Ice Age (1300 to 1800 A.D.). The results also show that present conditions are much drier than at any other time within this period. Xylem analysis is not only useful for determining patterns in rainfall through time but may also be useful in determining actual rainfall figures. In this regard the technique is unique for South Africa as the determination of actual rainfall figures is not possible for any other technique presently used in South African palaeoecological studies.

Since there are abundant assemblages of charcoal from archaeological sites in South Africa, the only limitations on this method of obtaining proxy rainfall data are the resolution of the radiocarbon dates, a suitable distribution of sites and a calibration curve for the species being analysed. While this method for rainfall reconstruction may prove useful in highlighting broad trends for rainfall change through time, it is the resolution of the time series in rainfall reconstructions within South Africa that does need to be addressed. This resolution is attainable with dendrochronology. In the Northern Hemisphere tree rings have demonstrated the capacity to produce long rainfall records (Fritts 1976 and Cook & Kairiukstis 1990). In South Africa several researchers have conducted some tree ring research (Hall 1976; McNaughton 1978; Curtis *et al.* 1978; McNaughton & Tyson 1979; De Fontaine 1991). All of these studies concentrate on *Podocarpus* sp. with very limited results. Despite this lack of success the focus has not changed over the years as is demonstrated by a recent conference (SASQUA 1993 conference) where two oral presentations focused on climate from the rings of *Podocarpus* sp.

In an attempt to assess the work of early researchers (Lilly 1977 and Curtis *et al.* 1978) as to the viability of *Podocarpus* for dendrochronological studies Chapter Five focuses on two *Podocarpus* species, *P. latifolius* and *P. falcatus*. The results indicate that even though whole trunk cross sections were used as advocated by Curtis *et al.* (1978) there is still a large percentage of error when calculating the age of these trees from ring counts. Combined with these results poorly defined, locally absent and converging rings makes cross-dating between different trees from the same locality an impossible task.

Dendrochronological methods are well established (Fritts 1976 and Cook & Kairiukstis 1990) but, within South Africa, only Dunwiddie and La Marche (1980) have conducted such a study. Most studies concentrate on counting or/and measuring ring widths, often of single trees, which are then related to climate. Dunwiddie and La Marche (1980) have developed a chronology for *Widdringtonia cedarbergensis* from the Cedarberg Mountains of the Western Cape Province of South Africa. *Widdringtonia cedarbergensis* (Chapter Six) differs from the various *Podocarpus* spp. (Chapter Five) in that age determination through ring counts is possible. However, 48% of the trees sampled at Krakadouw and 46% at Algeria were found to be unsuitable for analysis because of the lack of an abrupt termination of late wood growth and several false bands within the late wood. Despite this difficulty it is possible to cross-date (match ring width variations among trees) *W. cedarbergensis* trees from the same locality (Fig. 15). As demonstrated in Chapter Six the result of this cross-dating is the establishment of two more chronologies to add to the one established by Dunwiddie and La Marche (1980). The total number of chronologies for South Africa have thus increased from one to three, all on *W. cedarbergensis*. Notwithstanding this increase rainfall reconstructions were still not possible because correlations between ring width and rainfall are not sufficiently good. These results have, however, redirected the focus for future research in that neither *Podocarpus* nor *Widdringtonia* should be re-examined if dendroclimatology is the desired outcome since neither are suitable for such an analysis. Instead, the focus should be on developing new methods and ideas with different species.

Rather than develop new chronologies or embody new species the present study concentrated on the development of a new approach based on previous research which has shown that the stable carbon isotope ratios of tree rings are also good indicators of plant available water (Francey & Farquhar 1982; Freyer & Belacy 1983; Leavitt & Long 1989). With this emphasis, the relationship between water stress and tree rings for the Dunwiddie and La Marche (1980) chronology was examined in terms of stable carbon isotope ratios (Chapter Seven). This approach is based on the hypothesis that with increased water stress, stomatal closure results in reduced CO_2 uptake and therefore less discrimination which leads to more positive stable carbon isotope ratios (Francey & Farquhar 1982).

In the Northern Hemisphere a number of researchers have reported correlations between $\delta^{13}C$ values of tree ring cellulose and humidity (Ramesh *et al.* 1986; Loader *et al.* 1995), temperature (Stuiver & Braziunas 1987; Loader *et al.* 1995), soil water potential (McNulty & Swank 1995) and water use (Livingston & Spittlehouse 1993 & 1996). There are, however, only two established long rainfall records that have been based on $\delta^{13}C$ values of tree ring cellulose (Lipp *et al.* 1991 & 1994). At the Die Bos site water stress induced by high summer temperatures combined with low rainfall should lead to an abrupt termination of growth which would only be released with the onset of the winter rains. Rainfall in this region is strongly correlated with humidity and soil moisture both of which have been shown to be strongly correlated with tree ring $\delta^{13}C$ values (Stuiver & Braziunas 1987; Ramesh *et al.* 1986; Loader *et al.* 1995). As a result, the annual rings laid down by the tree should be directly related to cambial activity associated with specific rainfall years. There should therefore be a close correlation between $\delta^{13}C$ values of these annual rings and the rainfall of the corresponding year. Contrary to these expectations, however, there are no significant correlations between $\delta^{13}C$ values of tree ring cellulose and various combinations of monthly and annual rainfall from Wupperthal. This lack of correlation combined with the low correlations for dendrochronology suggest that water is not the major limitation to growth for *W. cedarbergensis*. Like many of the other species growing in the Fynbos Biome, *W. cedarbergensis* probably has a deep root system which allows it to maintain an association with water irrespective of rainfall (Stock *et al.* 1992; Richards *et al.* 1995).

What is reflected in the 100 year *Widdringtonia* $\delta^{13}C$ record is a strong correlation between isotope ratios of tree ring cellulose and atmospheric CO_2 levels through time. These results are similar to that derived from ice core data by Friedli *et al.* (1986), from maize kernel cellulose by Marino and McElroy (1991), $\delta^{13}C$ tree ring chronologies from the Northern Hemisphere (Freyer & Belacy 1983 and Leavitt & Long 1988) and recent Southern Hemisphere records (Leavitt & Lara 1994). This correlation is however, contrary to previous research for the Southern Hemisphere which shows no trend in $\delta^{13}C$ values over the last 100 years in Tasmanian tree rings (Francey 1981) or a trend which is half that of the Northern Hemisphere (Epstein & Krishnamurthy 1990). The first major chronology for the Southern Hemisphere to show a similar relationship to the Northern Hemisphere for tree ring $\delta^{13}C$ values and atmospheric CO_2 was that of Leavitt and Lara (1994) for a site in Chile. The results for *Widdringtonia* provide only the second chronology, the first with annual resolution, to show a decline in $\delta^{13}C$ values for the Southern Hemisphere which can be related to the anthropogenic impact on atmospheric $\delta^{13}C$ values.

Recent studies also suggest that plant $^{13}C/^{12}C$ ratios not only reflect atmospheric CO_2 levels but are also good indicators of water available to plants (Freyer & Belacy 1983 and Leavitt & Long 1989 & 1994). The results obtained for *Widdringtonia* in the present study are contrary to those obtained for other species by Freyer and Belacy (1983), Leavitt and Long (1989 & 1994) and others (Farquhar & Richards 1984; Hubick *et al.* 1986; Lipp *et al.* 1994). These contradictory results have defined a need to experimentally ascertain the relationship between $\delta^{13}C$ values, wood cellulose and water consumption of trees. Rather than resort to complex models and measurements of plant water demand, soil structure and climate the plants used in Chapter Eight were grown under controlled watering treatments. This allowed for direct correlations to be made between $\delta^{13}C$ values of wood cellulose and the amount of water used by the plant in two treatments. The results indicate that for both species carbon isotope ratios are significantly correlated with both water treatment and water consumption (Chapter Eight). The slope of the two graphs does depend on species but the trends are the same indicating that internal leaf CO_2 concentration (Francey & Farquhar 1982) increases with increasing soil water availability and with increasing water consumption resulting in more negative tree ring cellulose $\delta^{13}C$ values. The slopes of the two graphs are indicative of interspecies variability in $\delta^{13}C$ values which should be recognised and accounted for when conducting isotope research on different species from different localities.

These results suggest that the $\delta^{13}C$ values of wood cellulose may be useful in rainfall reconstructions, provided that the trees chosen for analysis are sensitive to changes in rainfall, that atmospheric isotope correlations are understood and that all environmental constraints are taken into consideration. These conclusions led to the next phase of the thesis which was a $\delta^{13}C$ analysis of the charcoal recovered from the archaeological sites Dzata, Mhlwazini Cave and Collingham Shelter (Fig. 23). The two most commonly identified woody species from these archaeological sites are *Combretum apiculatum* and *Protea roupelliae*. The results of previous research has shown that there is a strong correlation between wood anatomical variables and rainfall for *C. apiculatum* (February 1993). In the present study samples of this species collected along a rainfall gradient also show a positive correlation with $\delta^{13}C$ values. In contrast to this *P. roupelliae* wood cellulose shows no significant correlations between $\delta^{13}C$ values and rainfall (Chapter Nine). These results are contrary to expectations because earlier research (Chapter Four) has shown a very strong correlation between rainfall and wood anatomical variables indicating that for *P. roupelliae* cambial activity is indeed correlated with rainfall. If this is the case and the results as discussed for *Eucalyptus* (Chapter Eight) hold true, then there should be a correlation between $\delta^{13}C$ values of the wood cellulose of *P. roupelliae* and rainfall (Francey & Farquhar 1982; Freyer & Belacy 1983; Leavitt & Long 1989 & 1994; Lipp *et al.* 1991 & 1994).

In the neighbouring Fynbos Biome various researchers working with *Protea* species (Miller *et al.* 1983; van der Heyden & Lewis 1988) have not been able to detect plant moisture stress as indicated by xylem pressure potentials. They conclude that relatively high xylem pressure potentials during the hot dry summer months may be attributed to the rapid development of root systems in *Protea* seedlings allowing them access to deep soil moisture. This relationship is maintained as the plant matures and as a result, water stress is not a major limitation to the growth of *Protea* species (Richards *et al.* 1995). The $\delta^{13}C$ results for *P. roupelliae* are in agreement with this conclusion but the relationship between rainfall and vessel diameter is not (Chapter Four). These contradictory results may be attributable to the habitat of *P. roupelliae*. Unlike *Combretum apiculatum*, *P. roupelliae* grows in a wide variety of habitats and on a range of soil types and depths as well as in areas of very high rainfall. The sample was also collected over a distance of more than 1000 km from Umtamvuna in the south to Serala in the north (Fig. 23). It is possible that a range of ecophysiological factors and environmental variables may account for the variations in $\delta^{13}C$ values among trees from different locations. Since the objectives of the present study were to develop chronologies of rainfall through time, these apparent contradictory results should be the focus for future research. For this study, the non significant results suggest that *P. roupelliae* charcoal from archaeological sites may not be used in climate reconstructions.

Although the cellulose extract of *C. apiculatum* does show highly significant correlations for $\delta^{13}C$ values and rainfall, correlation is not maintained when wood is charred because pyrolysis degrades hemicellulose at temperatures between 200 and 300° C followed by cellulose above 240° C and lignin above 280° C (Prior & Gasson 1993). Thus the main components of wood are degraded at temperatures under 300° C. This rate of degradation is not constant with different pieces and species of wood reacting differently depending on a number of factors including size and location to heat source. This conclusion would suggest that a $\delta^{13}C$ analysis of charcoal from archaeological sites may not be useful for developing long rainfall records.

Focus for future research

The main contribution of this thesis toward the development of a long rainfall record for South Africa is in that it has focused future research on new species for dendrochronology and the development of a more substantial rainfall record from *P. roupelliae* archaeological charcoal.

Of the four techniques examined only xylem analysis shows any promise for providing a rainfall chronology that goes beyond the historic record. Much work still has to be done in this respect as this study has only analysed a few points within the last 2000 years. For *P. roupelliae*, however, a charcoal calibration curve now exists. This curve can be used to facilitate the rapid development of a rainfall chronology based on the *P. roupelliae* charcoal from archaeological sites. For any other species, however, a charcoal calibration curve will have to be developed prior to any development of a rainfall chronology.

Taxonomic identification of charcoal from archaeological sites is extremely useful in quantifying the extent to which people have influenced specific environments through time. The use of this type of analysis when establishing nature reserves and National Parks could be extremely useful for reserve management in that research efforts could be profitably designed to ascertain the true nature of the original vegetation prior to extensive human occupation or farming.

An integration of the results presented in this thesis has highlighted the difficulties faced by South African palaeoecologists in developing a long rainfall chronology. Despite the lack of clarity in the present data sets the study has focused on areas for future research in that it has raised many of the problems which have prevented the development of a good chronology. It has become clear that *Podocarpus* spp. and *W. cedarbergensis* should not be relied upon in future research but that further research should focus on new species such as *Canthium burtti* for which D. Stahle (pers. comm.) has recently developed a ring width index chronology from 1845 to 1995 which is significantly correlated with regional rainfall records. It is possible that a stable carbon isotope chronology from this species will correlate significantly with rainfall.

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